EXPOSURE-RESPONSE RELATIONSHIPS FROM RAILWAY NOISE IN THE PRESENCE OF VIBRATION

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DECLARATION

This work was performed as part of a project funded by the Department for Environment Food and Rural Affairs. However, the views and analysis expressed in this Thesis are those of the author and do not necessarily reflect those of the Department for Environment Food and Rural Affairs or the University of Salford research team.

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ABBREVIATIONS, DEFINITIONS, AND SYMBOLS

ABBREVIATIONS

CRN	Calculation of Railway Noise (Department of Transport, 1995)
BRM	Binary Regression Model
ORM	Ordinal Regression Model
LRM	Linear Regression Model
%LA	percent little annoyed
%MA	percent moderately annoyed
%HA	percent highly annoyed
%A	percent annoyed

DEFINITIONS

percent little annoyed	Percentage of those who report categories: “slightly”, “moderately”, “very”, and “extremely” in 5-point semantic scale or categories between “3” and “11” in 11-point numeric scale
percent moderately annoyed	Percentage of those who report categories: “moderately”, “very”, and “extremely” in 5-point semantic scale or categories between “6” and “11” in 11-point numeric scale
percent highly annoyed	Percentage of those who report categories: “very” and “extremely” in 5-point semantic scale or categories: “9”, “10”, and “11” in 11-point numeric scale
assessment	Any method used to calculate or predict, estimate or measure the value of a noise or vibration indicator or

	the related harmful effects;
annoyance	The degree of community annoyance as measured via two independent annoyance scales: 11-point numeric scale and 5-point semantic scale.
exposure-response relationship	the relationship between exposure to noise or vibration and annoyance
L_{den}	A-weighted long-term sound pressure level determined over 24h periods of a year
L_{day}	A-weighted long-term average sound level as defined in ISO 1996-2: 1987, determined over all the day periods of a year
$L_{evening}$	A-weighted long-term average sound level as defined in ISO 1996-2: 1987, determined over all the evening periods of a year
L_{night}	A-weighted long-term average sound level as defined in ISO 1996-2: 1987, determined over all the night periods of a year
$VDV_{b,24h}$	Velocity Dose Value calculated from a weighted vertical component of acceleration signal recorded for 24h time period
$RMS\ W_k$	Root Mean Square calculated from a weighted vertical component of acceleration signal recorded from 24h time period

SYMBOLS

i	A category for which percentage equivalence ($\%A$) is computed
m	A number of all categories
Var	Variance value calculated for a regression model
E	Expected value
ε	Error distribution around a mean value in a regression equation

L	Likelihood function
$C_{i,LU}$ $C_{i,HU}$	Lower and upper confidence intervals around a mean (expected value) superimposed in graphs illustrating exposure-response relationships
R^2	Goodness-of-fit for regression models
π	Probability of a cell of a contingency table
Ω	An odd value calculated between two conditional probabilities in a contingency table
θ	Odds Ratio value calculated for contingency tables
RR	Relative Risk value calculated for contingency tables

ABSTRACT

The main aim of this thesis is to develop exposure-response relationships for noise, vibration, and combined effects from noise and vibration. Examinations of non-acoustical factors such as noise sensitivity, noise acceptance, gender, age, and sleep disturbance are also performed in this project. Many studies have previously been conducted to investigate community response to transportation noise in residential areas. Comparatively few studies have investigated community response to vibration exposure, and fewer still the combined effects of noise and vibration. This study of exposure-response relationships for noise and vibration therefore presents a potentially significant need contribution for the problems of these kinds.

This work was performed as part of the Defra funded project "NANR209: *Human response to vibration in residential environments*" which was conducted between January 2008 and March 2011. The database for the project was obtained by undertaking a social survey questionnaire along with measurements of vibration. The project addressed railway, construction and internal sources of vibration. This thesis concerns railway exposure for which the database contains 931 cases. The face to face interviews took place within participants' dwellings. In 542 properties out of 931, internal vibration was recorded and calculated utilizing a number of vibration indices, two of which are $VDV_{b,24h}$ and RMS W_k. Vibration exposure has been predicted for the remaining cases. Noise exposure in the form of L_{den} has been calculated for 843 out of 931 cases using the Calculation of Railway Noise procedure (Department of Transport, 1995). It has been estimated that maximal error that can be expected from prediction in this thesis is equal to ±10 dB(A) at the 95% confidence level. On the other hand, maximal error that can be expected from vibration measurements is equal to ±2.2 dB or ±6.2 dB, with regard to "internal measurements" and "no measurements", respectively.

It is concluded from analyses of combined effects that noise and vibration additively contribute to the proportion of people reporting little, moderate, and high annoyance from exposure to railway noise in the presence of vibration.

[Work funded by the Department for Environment, Food and Rural Affairs (Defra) UK]

1. INTRODUCTION

This document summarizes the results from investigation of the relationship between noise and vibration annoyance due to railway traffic. As annoyance is not a simple problem to analyse, different potentially influential factors were also analysed. As expected, large amount of variation is unexplained when one considers exposure-response relationship. Following this issue, additional non-acoustical factors are also investigated in this work such as

- Age
- Gender
- Noise sensitivity
- Noise acceptance
- Sleep disturbance

Noise plays the most important part of this research. However, besides noise, residents are also exposed to different kind of phenomena. Figure 1 illustrates a couple of paths that vibration and noise propagate towards a property. As can be seen, the most obvious is the air borne noise propagating using air medium. According to the picture, it is considered the primary noise source (transmitted external noise). The primary noise is attenuated by walls. Nevertheless, the strength of attenuations depends on size and material that walls can be made of.

Apart from primary noise, residents are also exposed to ground borne vibration and then structure borne vibration when a building starts to vibrate. The propagation along the path from source to a receiver is a complex problem to model. Therefore, in majority cases, vibration has been measured inside properties or at least at closest to a property. Developing a novel methodology avoided such problems. It was possible to determine a large number of events from direct internal vibration measurements and remaining number of events from the prediction.

Because of vibration of a structure, residents may also be exposed to structure borne noise. In this work, combined effects from primary external noise and structure borne vibration are taken into account during analysis. Unfortunately, due to constraints, it was not feasible to undertake analysis on problems regarding structure borne noise. This may be one of the primal problems when transportation is located in tunnels.

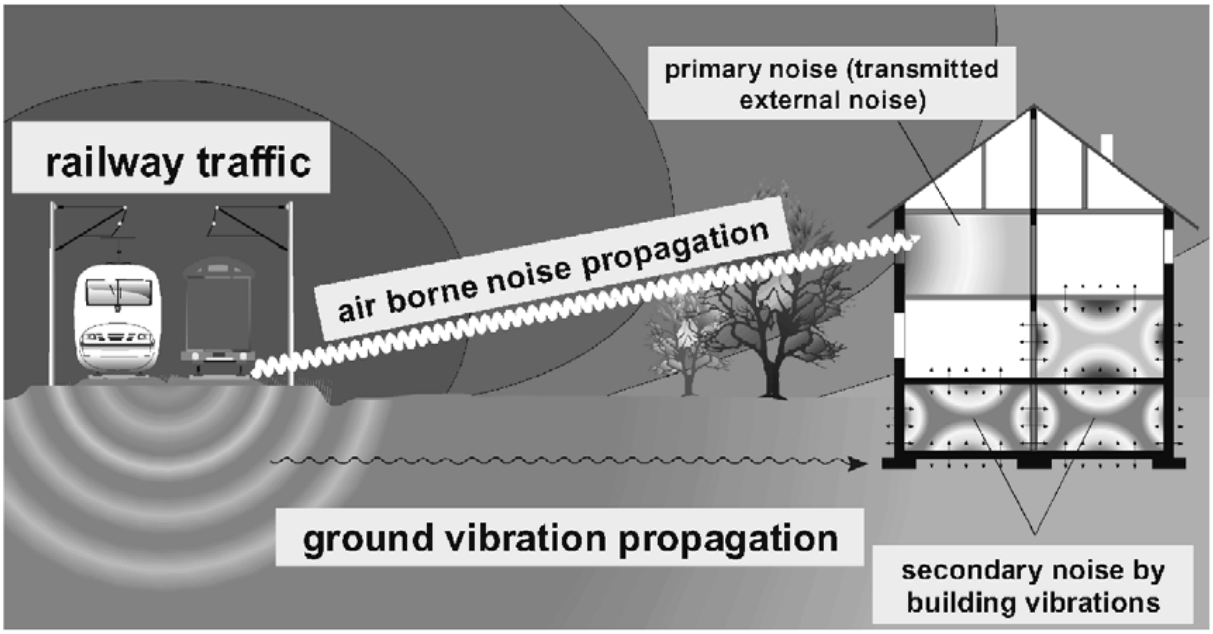

Figure 1. Illustration of the complex exposure residents are affected by (Thompson, 2009).

Noise exposures could not be obtained via measurement but calculated using the Calculation of Railway[1] (Department of Transport, 1995). It was not feasible to anticipate all possible variations regarding each site. There were 843 out of 931 residents that noise exposure has been calculated for. Calculations involve mainly passenger trains, although freight trains were also included. An accurate number of freight trains passing residents' facades was one of the most difficult factor to estimate. Nonetheless, the number of freight trains was obtained via a digital signal processing algorithm operated on an acceleration signal recorded for 24h time period. The detection was based on the length of a particular event. Since this will not exactly reflect the real number of trains occurring during a period of vibration measurements, noise exposures vary if compared to real values. Therefore, uncertainties have also been included in the analyses to provide confidence intervals that compensate errors from prediction.

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[1] This name is abbreviated as CRN through the whole thesis.

During the work, it is thought that following objectives have been achieved:

- Estimation of noise exposure calculated for 843 out of 931 cases
- Field work and internal vibration measurements conducted for 542 cases out of 931
- Exposure-response relationship was developed for human response to transportation (railway) noise in residential environments
- VDV and RMS were estimated from acceleration signals measured during the field work
- Combined noise and vibration exposure-response relationship indicates that for given noise and vibration exposures, reported annoyance increases
- Factors influencing annoyance; due to noise exposure from railway, sleep disturbance was found to be the most important issue followed by age and noise acceptance; gender and noise sensitivity are not found to be influential factors on annoyance.

The document is split into six chapters followed by appendices. A literature review is presented on determination of noise exposure, determination of vibration exposure, determination of noise and vibration exposure, community response to noise, community response to vibration, and finally community response to noise and vibration.

The third chapter explains the methodology used in this analysis. The analysis concerns community response in the presence of exposures. Regression models have been found most appropriate. Consequently, linear and logistic regression models have been outlined in this chapter with justification of the most adequate regression model. Due to the large number of categorical variables included in the analysis, a small section covers also an explanation of a technique called the Odds Ratios.

The fourth chapter gives detailed information on applied metrics with regard to noise and vibration. This chapter gives an explanation of the L_{den} used to express noise exposures. A short discussion on application of L_{den} and its accuracy has also been included. Due to additional analysis of effects from vibration with association to response, this chapter also provides an outlined description of the main indices used during measurement and calculation of vibration exposure along with summary from other reports associated with project “Human response to vibration in residential environments”. This is followed by an examination of uncertainty evaluations for both noise and vibration exposure.

The fifth chapter covers analysis regarding noise and vibration as separated stressors and analyses are provided in terms of combined effects from both exposures. The Thesis ends with conclusions in chapter six and possible further work addressing improvement of analysis and additional ideas which could not be finished mainly due to lack of time.

Appendices include explanation of the annoyance phenomenon, procedure according to which vibration measurements were conducted, Ethical Approval of social survey questionnaire, and a few considerations regarding Principal Component Analysis.

It is important to mention that Ethical Approval has been accepted on the 23rd of April 2008.

2. LITERATURE REVIEW

2.1. INTRODUCTION

A literature review is presented in this section. It begins with outline of international standards. A brief explanation of vibration, which is a part of this project, is also provided. It is followed by review of other work related to determination of exposure-response relationship for community response to noise, vibration, and response to combined effects from noise and vibration. Finally, the section concludes with review on work related to statistics commonly used by researchers to investigate community response to noise and vibration exposure.

2.2. DETERMINATION OF NOISE EXPOSURE

CRN[2] (Department of Transport, 1995) describes the procedure of estimating noise from railway traffic sources. Although published sixteen years ago, this document is still widely considered to be the best predictive method of assessing railway noise. Additionally, Railway Noise Source Terms For "Calculation of Railway Noise 1995" (Department of Transport, 2007) provides complementary information pertaining to noise emission.

The accuracy of noise estimation procedures may suffer due to a number of errors (Hepworth, 2006). The main points identified are errors in calculation methodologies, implementing methodologies, errors in input data, errors introduced in processing data for noise mapping, and errors introduced in the software calculation of noise levels. For noise mapping, noise emissions from vehicles are calculated for every residence within in area affected by noise pollution. Errors could be evaluated as a calculation of uncertainty (Craven et al., 2001).

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[2] Calculation of Railway Noise is denoted as CRN through this document

In this project, emphasis was placed upon investigation of external exposure. Acousticians make opposite points about correlation between indoor and outdoor exposures. On one hand, when internal exposure is considered, Shield et al. (2004) discusses problems of internal exposure to environmental noise inside classrooms at schools. Shield et al. (2004) review the problem regarding correlation between external noise and internal exposure and conclude that not sufficient information can be found on this matter.

On the other hand, internal exposure from transportation noise was investigated by Graham et al. (2009) who applied different methodology of noise measurement. During night-time measurement, a single external monitor and up to twelve internal monitors were installed depending on the number of houses per location. The difference between external and internal levels was then calculated using a selection of hundred of the loudest and quietest individual noise events subjected to the least contamination from internal noise sources. The results indicate a good relationship between indoor and outdoor exposures (Graham et al., 2009). Two British Standards (BS 8233:1987) and (BS EN 12354-3:2000) provide methodology on estimation internal exposure based on external measurement.

The data were obtained from 18 study areas in cities. The main objective was to The European Union's Environmental Noise Directive (Directive 2002/49/EC, 2002) states that a common noise indicator for assessing annoyance is L_{den} (sometimes denoted as DENL)--the noise index is defined in section 4.5.1, and sleep disturbance may be assessed using the L_{night} metric (See section 4.5.1). It is also useful to provide supplementary indicators in order to monitor or control more complex situations during noise exposure or combination of a number of sources. A common approach is to determine exposure to noise in relation to annoyance response determined by either L_{dn} (sometimes denoted as DNL) or L_{den} (sometimes denoted as DENL).

According to suggestions from EU Directive (Directive 2002/49/EC, 2002) and research presented by other papers (Miedema et al., 2007; Van den Berg et al., 2002), L_{den} appears to be the most common noise measurement metric for railway sources.

Marquis-Favre, Premat, and Aubrée (2005) argues about very weak correlation between annoyance and noise metrics such L_1, L_{10}, L_{den} etc. The maximum value of Spearman correlation was found to be 0.35. Guski (1998) and Berglund (1998) state that about 30% of variance can be accounted for noise exposure expressed via L_{Aeq}. According to

Job (1988) and Lercher (1998), this value is less than 20% while using the energetic rating L_{dn}. Therefore, besides acoustic parameters such as energy, duration, or frequency composition of signal, the existing variance not explained by acoustics factors has to be explained by something else. It is suggested that other non-physical annoyance factors, that are linked to attitude, personality and other socio-psychological and socio-demographic variables can describe the remaining variance. Fields et al. (1997) talks about demographic, attitude and situational variables (Marquis-Favre, Premat, Aubrée, et al., 2005).

The examination of literature shows the expression of noise exposure is followed by average sound levels: L_{dn} and L_{den}. Fidell (2003) argues the accuracy of implementing these two noise indices in first place, yet concludes that for the time being indices were the most common measures to determine noise exposure.

In this work the choice of L_{den} was rather dictated by the method of predicting noise exposure. On one hand, since CRN provides a well known methodology and procedure to predict noise levels in given circumstances, CRN was applied to calculate noise exposure for 931 cases but simultaneously limits the application of just one noise index L_{dn}. In terms of transportation noise, EC (Directive 2002/49/EC, 2002) suggests L_{den} as a more preferable metric. Because calculation of L_{den} does not vary from calculation of L_{dn}, the procedure was adjusted in order to express noise exposure using L_{den}.

In the Position Paper by Van den Berg et al. (2002), Henk Miedema summarises the recommended descriptors of noise exposure and annoyance along with exposure-response relationship curves. These curves were recommended for use in the context of the proposal for a Directive on the Assessment and Management of Environmental Noise. L_{den} was therefore established as a standard regarding exposure-response relationship to transportation noise. The paper by Van den Berg et al. (2002) also refers to percentage of highly annoyed and states that

> "An advantage of percentage measures such as %HA and %A over the average annoyance is that the corresponding prevalence measures (number of highly annoyed persons, number of annoyed persons) are more easily understood by the public than prevalence measures on the basis of the average annoyance (noise annoyance index)" (Van den Berg et al., 2002, p. 3).

The latter document presents the application of average sound level L_{den}. This report is important due to the European standard model described by Miedema (2007).

One of the first applications of L_{dn} can be found in the pioneering study by Schultz (1978). In this preliminary work, noise exposure from aircraft, street traffic, express traffic, and railway traffic was examined with relationship to annoyance, spanning a period of fourteen years and a range of nine countries. Based on findings regarding dose-effect in 1970s (Fidell, 2003), the noise exposure L_{dn} appeared to be most common measure of noise exposure averaging sound energy along twenty four hours and implying penalties due to evening and night time periods. In Shultz's paper (Schultz, 1978), the application of L_{dn} seems to work because of a good correlation range and annoyance scales--in fact, in one of the studies, Shultz found that correlation varied between 0.44 and 0.52 with windows closed and 0.87 with windows open.

2.3. DETERMINATION OF VIBRATION EXPOSURE

The vibration exposure is included in analysis as a second stressor in this project. A detailed explanation of determination of vibration exposure was given in *Technical report 3: Determination of vibration exposure*(3) (Sica et al., 2011). It can be read that different standards are applied in many countries to determine the vibration exposure: United Kingdom with (BS ISO 6472-1:2008), United States with FTA guidelines with FTA 2006 (), Norway with (NS 8176:1999), Sweden (DNR.S02-4235/SA60), and Germany with (DIN 4150-2:1999).

Time limits and number of measurements dictated the methodology of measurements of vibration exposure (Peris et al., 2011) and calculation of vibration exposure (Sica et al., 2011). Both methodologies were adapted to fulfil the main objectives of the Defra project. The report by Sica et al. (2011) describes the methodology of measurements conducted externally and internally.

Two vibration metrics have been used to express for vibration exposure such as $VDV_{b,24h}$ (BS ISO 6472-1:2008, 2008) and RMS W_k (ISO 2631:1997) both expressing vibration over twenty four hour time period. The use of these metrics is also found in the report by Woodcock, Peris, et al. (2011) where determination of exposure-response relationships is explained for the Defra project "*Human response to vibration in*

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[3] The Defra funded project "NANR209: *Human response to vibration in residential environments*" was explained in a document divided into following reports: "Executive Summary", "Final project report", "Technical report no 1" , "Technical report no 2" , "Technical report no 3" , "Technical report no 4" , "Technical report no 5" , "Technical report no 6".

residential environments". As described elsewhere (Section 4.3.1), due to ease of application and recommendation in European (ISO 2631:1997) and British (BS ISO 6472-1:2008, 2008) standards, *VDV* and *RMS* were considered the most relevant for vibration exposure.

2.4. COMMUNITY RESPONSE TO NOISE EXPOSURE

Community response to noise especially from transportation has been studied for several decades by many researchers. The process of investigation on this subject is still in progress. A significant number of papers regarding noise exposure and community response are available. The purpose is to provide a process of development of this problem and consequently establish a solid base.

Although a wealth of literature is available, the work of Schultz (1978) is considered to be one of the first papers in which an attempt was made to establish exposure-response relationship to transportation noise. Schultz collected and reviewed eleven social surveys from nine countries with regard to noise from aircraft, street traffic, express traffic, and railway traffic spanning a period of fourteen years. An attempt was made to make investigation comparable and obtain a prediction of annoyance and noise exposure. Schultz synthesised all the clustering survey results and constructed curves showing the relationship. The curves illustrating "percent highly annoyed" against L_{dn} were fitted by third order polynomial. Annoyance scales could not be directly compared in their original form due to different annoyance scales. Consequently, Schultz converted all the scales into their percentages equivalence. Those who were "highly annoyed" became those who reported the upper 28% in the annoyance scale. L_{dn} was chosen to express noise. Schultz (1978) has selected "percentage highly annoyed" (%HA) for annoyance measure because, as postulated, "the effects of non-acoustical variables are reduced, and the correlation between the noise exposure and the expressed subjective reaction is high, both for individuals and for groups." Another argument for choosing "highly annoyed" over mean or median was related to the fact that it was not certain whether noise exposure data was obtained from direct, shielded or reflected sound. Finally, the relationship between noise exposure and %HA was found to be highly consistent between the studies. The magnitude of noise exposure increased with annoyance reported by respondents. Fidell et al. (1989) conducted a similar analysis including four studies with 292 additional data points. Fidell et al. (1989) concludes that his curves are similar to original Shultz's curves.

The Schultz's curves opened the criticism which did not meet the agreement in that time. Kryter (1982) makes a point about combining together all the transportation noise sources, whereas they should be distinguished explicitly. Kryter (1982) argues about significant underestimation of the annoyance associated with aircraft noise and overestimation of the percentage of U.S. population exposed to transportation noise level" (Kryter, 1982).

Miedema et al. (2001) analysed the same data as Schultz (1978) along with additional surveys from Fields (1993) giving in summary the number of 55 studies with 63,936 respondents. Miedema states that in previous papers "most publications used only a limited number of studies, or did not pay much attention to the comparability of the definition of variables in different studies" (Miedema et al., 2001). The curves presented in this article show the exposure-response relationship for transportation noise sources separately: road traffic compared with aircraft traffic and road traffic compared with railway traffic. Due to limited number of data, only two groups of transportation noise could be compared. To investigate the interaction between studies, the presented curves were obtained by conducting two separated statistics: standard least squares regression analysis and multilevel approach. The case selection is conducted in two stages: first the study and then the case within each study. Also, an improved exposure-response model is presented by Miedema et al. (2001). Analysis is based on the same data which can be found in the work of Schultz (1978). The model is applied in a later paper (Groothuis-Oudshoorn et al., 2006) and presents exposure-response curves along with confidence intervals. This model brought improvements into relationship because of modelling entire annoyance distribution or calculating standard error giving robust–confidence limits.

Klæboe et al. (2004) investigated "modifying factors" such as age and noise sensitivity and concluded that these factors the most important modifying variables. Klæboe et al. (2004) also concluded that variables such as gender, having young children, marital status, and education level were not found to substantially contribute. These latter findings are in accordance to Miedema et al. (1999) and Fields (1993). Fields (1993) postulates that annoyance is not affected by any of nine demographic variables such as age, sex, social status, income, education, home, ownership, type of dwelling, length of residence, or receipt from the noise source but is related to five attitudes such as fear of danger from noise source, noise prevention beliefs, general noise sensitivity. Fields (1993) did not find clear evidence that age has influence on annoyance, in opposed to (Gerven et al., 2009) and (Groothuis-Oudshoorn et al., 2006). From these papers, it can be seen that age has a clear influence on annoyance when age is between forty and fifty years.

The literature shows that the strongest influence on annoyance have fear and noise sensitivity. Miedema et al. (1999) investigated the effect of noise sensitivity and state that this effect is significant. Therefore, a better understanding this mechanism could be important. To investigate this problem, two scenarios were considered in this paper: “sensitivity has an independent effect on annoyance, which adds to the effect of the noise exposure” and “noise sensitivity alters the effect of the noise exposure” (Miedema et al., 1999). Another objective of this paper was to investigate whether noise sensitivity “influences reactions to environmental conditions other than noise (e.g. odour)”. In conclusion, noise exposure has very small effect on noise sensitivity, whereas noise sensitivity has a large influence on annoyance. It can be read that, by definition, noise sensitivity is a personality trait: it is stable but decreases over time and it is invariant over different conditions. Sleep disturbance was not related at low level noise. However, at higher levels, the influence becomes stronger. Consequently, noise sensitivity relates to such as self-reported sleep disturbance.

Fear, an attitudinal effect, is said by one group of researchers to be the most influential, non-acoustic effect on annoyance (Fields, 1993), although the others show no impact. From literature reviewed Marquis-Favre, Premat, and Aubrée (2005), the fear is mentioned as an important factor because its excessive level might cause a hearing impairment. If the same level of noise is compared with group of respondents who revealed fear and did not reveal fear, the annoyance was significantly higher when fear was present. The link between fear and annoyance is uncertain (Fields, 1993). On one hand, it is reported by Kryter (1982) and confirmed by Miedema et al. (1998) that there is the link between fear and annoyance. On the other hand, Vallet (1996) states that although this factor reveals its negative influential impact on annoyance, it differs on its estimation.

2.5. COMMUNITY RESPONSE TO VIBRATION EXPOSURE

Vibration exposure has not been excessively investigated comparing to noise. Woodroof et al. (1987) conducted a field survey in Scotland where railway caused vibration in buildings. Along with measurements of response via questionnaires, vibration was measured in a number of buildings. Another study was conducted in the United Kingdom by the Transport Research Laboratory (Watts, 1984). Residents from 50 sites were asked about the disturbance from vibration induced by railway traffic. Vibration measurements were conducted internally and externally at respondents' properties.

In Norway, community response to noise and vibration induced by road traffic noise was investigated by Klæboe (Klæboe, Öhrström, et al., 2003; Klæboe, Turunen-Rise, et al., 2003) and Turunen-Rise et al. (2003). Questionnaires were conducted via telephone interviews. It was found that people were exposed to a vast range of vibration velocity values ($v_{w,95}^{(4)}$ 0 – 3 mm/s). Vibration exposure in each residence ($v_{w,95}$) was estimated via a semi-empirical model (Madshus et al., 1996). The exposure-response relationship was analysed via a logistic regression model. Generally, it was found that annoyance increases when vibration exposure is greater. It was also found that there were no differences between annoyance cased by vibration exposure from road traffic or railway. In these studies, relationships were also reported for disturbance of activities such as communication and watching TV.

Transit Cooperative Research Program (Zapfe et al., 2009) is one of the recent studies on community response to ground-borne vibration induced by trains. The study was conducted in North America and Canada "with a view to developing criteria for acceptable levels of railway induced ground-borne noise and vibration in residential buildings" (Woodcock, Peris, et al., 2011). In the report by Zapfe et al. (2009), about 200 different noise and vibration metrics were considered as potential independent variables for an exposure-response relationship. Woodcock, Peris, et al. (2011) also calculated numerous descriptors of vibration exposure from 24-haour acceleration time histories of internal vibration. In the report by Woodcock, Peris, et al. (2011), it was confirmed via application of Principal Component Analysis and Spearman correlation between descriptors and self reported annoyance that a type of descriptor is not

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[4] This metric is determined from the mean and standard dev. of the individual event weighted RMS velocity at a specific location. The interpretation of this is that there is a 95% probability that a measurement of train vibration will fall below the $v_{w,95}$ (Zapfe et al., 2009, p. 19). $v_{w,95} = v_{w,mean} + K\sigma$. (K = 1.8)

important. This is consistent with conclusion found in the report by Zapfe et al. (2009). The choice of vibration descriptors were finally dictated by ease of calculation, interpretability, current practice, and the measurement capability of the user of the exposure-response relationship.

This Thesis explains the response to noise exposure with and without the presence of vibration. The comprehensive literature review on vibration exposure can be read in *Technical Report 3*[3] (Sica et al., 2011) and *Technical report 6* (Woodcock, Peris, et al., 2011).

Peris et al. (2012) has analysed the proportion of highly annoyed changing in different time periods. Peris et al. (2012) concluded that for the same level of vibration exposure, the highest proportion of annoyed was found during night-time period, followed by evening-time, and day-time. For instance, for vibration exposure RMS W_k = 0.001 m.s^2, proportion of highly annoyed would be 2.5% during the day-time, 4% during evenings, and 8% during night-time periods. For the maximal considered vibration exposure RMS W_k = 0.01 m/s^2, these numbers rise as follows: 5% during the day-time, 8% during the evenings, and 20% during the night-time. Due to variations in proportion of highly annoyed in different time periods, Peris et al. (2012) investigated the application of additional penalties (similar to calculation of L_{den}). In this paper, it has been postulated that two weighting factors should be applied to overall equation for calculation of $a_{w,den}$. As such, the overall equation has the form

$$a_{w,den} = \sqrt{\left(a_{w,07:00-19:00}\right)^2 + \left(w_e a_{w,19:00-23:00}\right)^2 + \left(w_n a_{w,23:00-07:00}\right)^2} \qquad (2.1)$$

where $a_{w,den}$ is the total day–evening–night frequency-weighted RMS acceleration, $a_{w,7:00-19:00}$ is the day frequency-weighted RMS acceleration, $a_{w,19:00-23:00}$ is the evening frequency-weighted RMS acceleration, $a_{w,23:00-7:00}$ is the night frequency-weighted RMS acceleration and w_e, w_n are the time of day weights equal to 6.7 and 50 respectively (Peris et al., 2012).

2.6. COMMUNITY RESPONSE TO NOISE AND VIBRATION

Annoyance from exposure to noise and vibration has already been investigated by Öhrström et al. (1996). Öhrström et al. (1996) concludes that people are no longer exposed only to one noise source, but combination of two or even three sources. The project TVANE was based on investigation previously conducted by Miedema et al. (2001), Kaku et al. (1996), and Öhrström et al. (1996). The problem of combined effects from exposure to noise and vibration is complex but does show that the annoyance invoked by noise is increased when vibration occurs (more intensively during strong vibration > 0.4 mm/s) (Ögren et al., 2009).

Problem of how much more annoying is noise from trains could be compared to noise from road traffic or air traffic. Öhrström et al. (2009) calls this problem was "railway bonus". Öhrström et al. (2009) makes a point that "railway bonus" can vary from one to another areas such as different continents or even different countries. Laboratory experiments can be conducted in a more controlled environment but field studies can give more realistic results.

The problem of simultaneous interactions between noise and vibration exposure was observed in laboratory studies (Howart et al., 1990; Howarth, 1991; Howarth et al., 1990; Paulsen et al., 1995). Subjects were exposed to simulated noise and vibration as if they were emitted by railway. Six magnitudes of vibration and noise were investigated. Similar experiments were conducted by Öhrström et al. (2009) and Öhrström et al. (2008). It has been found that magnitude of noise exposure have a significant effect on the judgment of annoyance caused by vibration. No significant effect of vibration exposure was found on the judgment of annoyance caused by exposure to noise.

The similar study was conducted by Paulsen et al. (1995). Briefly, it was found that if subjects were asked to judge annoyance caused by vibration, then their annoyance judgments for a given vibration exposure were largely independent of the magnitude of noise exposure. However, it was found that if subjects were explicitly asked about annoyance due to noise exposure the magnitude of vibration exposure had an influence on their annoyance rating.

2.7. SUMMARY

In this a section, the literature review has been provided to establish the ground on which the problems in this project have been analysed. Noise exposure is the main part of analysis of exposure-response relationship to combined effects. The reviewed papers show a large number of applications of L_{den}. The most important is the report providing suggestions on this ground (Directive 2002/49/EC, 2002). Based on this guideline, the annoyance curves illustrating the exposure-response relationship to noise have also been established with relation to L_{den}. Calculation of Railway Noise provides the routine in establishing noise exposure from prediction. As this procedure provide exposures via L_{dn}, this procedure had to be adjusted to fulfil the guideline set from EC (Directive 2002/49/EC, 2002) and express the noise exposure by L_{den}.

Summarizing the discussion on the quality of noise indices, L_{den} may not be accurate if exposure-response relationship is considered. The main point made about this issue is related to variation accounted for noise and annoyance. It has been argued that the percentage of variation is too small when noise is expressed by L_{den}. In conclusion, the variation of relationship between noise and annoyance might be improved if aforementioned factors are included. A number of factors (demographic and attitudinal) have been considered. Due to the issues related to L_{den}, the factors have become even more important in the analyses. The time constrains however prevent from detailed investigation of their influence. Therefore, a subset of the factors has been taken into account. In the line of conclusion, the literature shows some factors that do have influence on annoyance (age, fear, and sleep disturbance to count just a few).

In conclusion on vibration, exposure-response relationship to vibration has not been not as widely studied as exposure-response relationship to noise. In the literature reviewed, the main objectives are directly related to human response. As such, vibration indices were also studied with regard to annoyance. The factors which are taken into account are sleep disturbance and fear. The damage of properties would become the most important. Vibration was also investigated with combination to noise. Similar to vibration, combination of noise and vibration can negatively influence on sleep disturbance. A number of papers regarding combined effects from noise and vibration exposure were provided in this section.

3. METHODOLOGY

3.1. INTRODUCTION

The exposure-response relationship can be explained as the way of presenting noise or/and vibration changes against a response. People can be affected by physical phenomena such aforementioned noise, vibration, or even odour. Annoyance is the form of response when people express dissatisfaction. The different response can be expected before and after exposure occurrence. The difference in exposures changes versus difference in response changes is called exposure-response relationships The purpose of the project is to establish exposure-response relationships between noise, vibration, and annoyance.

The analysis of problems of these kinds requires statistic methods including regression models (Groothuis-Oudshoorn et al., 2006; Klæboe et al., 2004; Öhrström et al., 2008). Two very popular models such as multiple grouped regression and ordinal probit regression[5] models are utilized. The analysis in this project is based on ordinal probit model but a multiple grouped regression model is also presented as it became a European guideline (Miedema et al., 2001; Van den Berg et al., 2002).

This chapter also introduces five-point semantic scale and eleven-point numeric scale to two annoyance scales as a measure of response. Both scales are shown along with their percent equivalence. The purpose of latter approach is found to be important due to the convenience to compare this study with the others found in literature.

The chapter is split into sections. The first section explains important terms regarding measurement of response such as thresholds indicating percent little, moderately, and highly annoyed. The second section presents the basis of regression models used in the

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[5] Ordinal Probit Regression and Ordinal Logistic Regression models vary from each other only by the distribution of error (residuals); if the error distribution has a Normal character then regression model is named to be “Probit”; if on the other hand the distribution has logit character then regression is named as “Logistic”

study with a comparison to linear regression model also common in literature. The last chapter presents a technique used to analyse association between categorical variables such as, response and noise sensitivity. This technique is called Odds Ratio--it is common in analysis of contingency tables with categorical data.

3.2. EXPLANATION ON RESPONSE MEASUREMENT

In this study, response to both noise and vibration, one of the components of exposure-response relationship, was measured in two scales. In five-point semantic scale, each category level is expressed as follows: "Not at all", "Slightly", "Moderately", "Very", "Extremely". The dependent response variable is ordinal. The eleven-point numeric scale is expressed by numbers starting from category "0" and ending with category "10". Both scales are assumed to be equally distributed along the categories meaning intervals between each adjacent categories remain the same.

Before the decision was made, a number of annoyance scales was taken into account. In technical report 2(3) (Condie et al., 2011b), it can be read that there is no consensus on which type of scale should be used to measure the relationship between exposure to noise, vibration, and annoyance. Many scales can be applied with the similar successful effect. Six characteristics based on Field (2001) were therefore taken into account while developing the measure of response to vibration and noise (Condie et al., 2011b):

- Provide a high quality, reliable measure of a general reaction to vibration annoyance in a residential environment;
- Yield an interval-level measurement scale able to meet the assumptions for regression and many other analysis techniques;
- Be suitable for face-to-face questionnaire administration
- Permit valid international comparisons of survey results within and between languages;
- Yield transparent results that will be consistently interpreted by survey respondents, policy makers and report readers; and
- Take the approach that is most likely to be adopted internationally.

For socio-acoustics survey designs, five-point semantic and eleven point numeric scales are recommended by standard (DD ISO/TS 15666:2003) and Fields et al. (2001). Additionally, eleven-point numeric scale is recommended by Nordtest Method (2001) for socio-vibration survey design. The use of five point semantic scale can likely be found in literature (Herranz-Pascual et al., 2009; Klæboe, Öhrström, et al., 2003; Lee et al., 2008) and in the standard (DD ISO/TS 15666:2003).

The Table 1 and Table 2 present cross-tabulations of two categorical dependent variables. In each cell, Table 1 contains a number of participants reporting noise annoyance whereas Table 2 contains a number of participants reporting vibration annoyance. This kind of tables reveals a number of participants who report the same two categories in five-point and eleven-point scales. For instance, a number of those who reported simultaneously "Not at all" in 5-point semantic scale and "0" in 11-point numeric scale is 447.

Both tables are included to confirm that annoyance degrees expressed in both scales provide very similar results. The diagonals of both tables contain certain frequencies different from 0. The further is a cell from each of the diagonals, the lower frequency number is observed. In both tables, at extreme columns and rows ("Not at all" by "10" and "Extremely" by "0"), the numbers are equal to zero. This is the expected effect, because otherwise both category scales would show inconsistency or a lack of association. Simply, participants would report different degrees in annoyance using different scales.

Table 1. Crosstab of two annoyance scales from noise section of questionnaire for railway sources

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not at all	447	80	28	7	7	4	1	1	1	1	0
slightly	3	13	39	36	21	20	5	4	0	0	0
moderately	0	1	1	4	14	35	25	20	10	1	2
very	0	0	0	0	1	4	7	13	27	12	3
extremely	0	0	0	0	0	1	0	2	8	4	19
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not at all	48.0%	8.6%	3.0%	0.8%	0.8%	0.4%	0.1%	0.1%	0.1%	0.1%	
slightly	0.3%	1.4%	4.2%	3.9%	2.3%	2.1%	0.5%	0.4%			
moderately		0.1%	0.1%	0.4%	1.5%	3.8%	2.7%	2.1%	1.1%	0.1%	0.2%
very					0.1%	0.4%	0.8%	1.4%	2.9%	1.3%	0.3%
extremely						0.1%		0.2%	0.9%	0.4%	2.0%

N = 932. $\chi 2$ (40) = 1708, $p < 0.0001$

Table 2. Crosstab of two annoyance scales from vibration section of questionnaire for railway sources

	0	1	2	3	4	5	6	7	8	9	10
not at all	533	53	31	17	11	4	4	2	1	1	0
slightly	6	8	28	36	25	9	2	3	1	0	0
moderately	0	0	1	4	9	24	24	14	5	2	0
very	0	0	0	0	2	2	3	12	21	11	3
extremely	0	0	0	0	0	0	1	0	3	2	14

	0	1	2	3	4	5	6	7	8	9	10
not at all	57.2%	5.7%	3.3%	1.8%	1.2%	0.4%	0.4%	0.2%	0.1%	0.1%	
slightly	0.6%	0.9%	3.0%	3.9%	2.7%	1.0%	0.2%	0.3%	0.1%		
moderately			0.1%	0.4%	1.0%	2.6%	2.6%	1.5%	0.5%	0.2%	
very					0.2%	0.2%	0.3%	1.3%	2.3%	1.2%	0.3%
extremely							0.1%		0.3%	0.2%	1.5%

N = 932. χ^2 (40) = 1831, $p < 0.0001$

Two ordinal scales in their original levels as well as their percent equivalences are shown by Figure 2. The second representation (percentage) is included because of a number of studies found in literature which involve this representation of annoyance scale; annoyance degrees in this scale are illustrated by majority of figures in a chapter discussing results (See 5). The percent annoyed is expressed by numbers between 0% (no annoyance reported) and 100%.

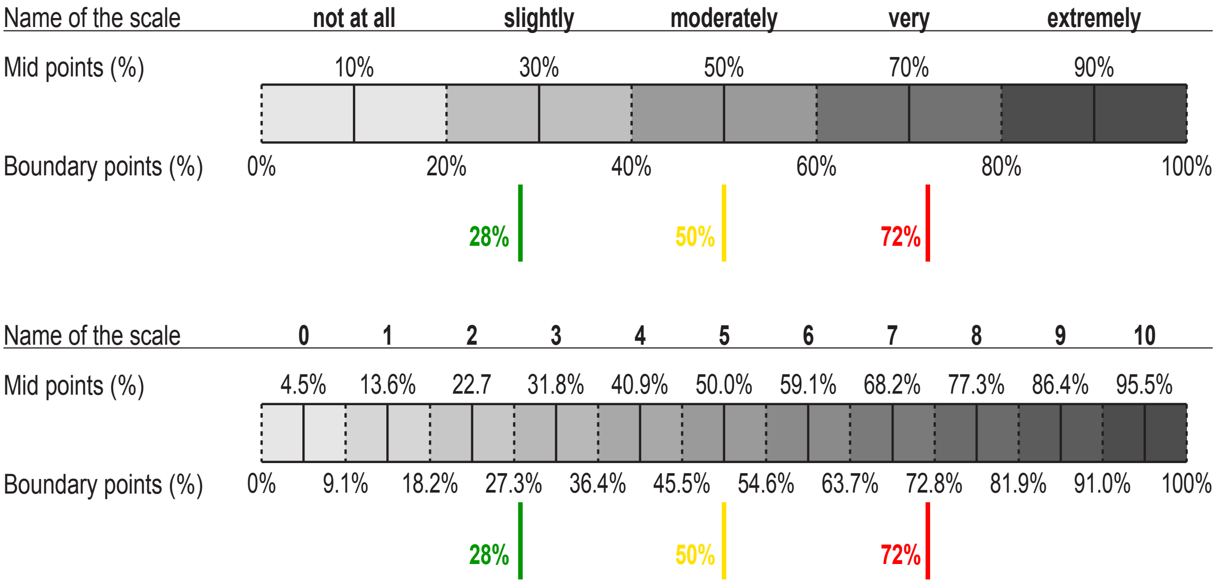


Figure 2. Two annoyance scales drawn with three thresholds representing percent little annoyed, percent moderately annoyed and percent highly annoyed

The percent scales, however, reveal one important problem. The particular percentage shown in green, yellow, and red colours correspond to three thresholds. These thresholds indicate so-called cut-off points that determine proportion of participants reporting annoyance degree higher than a particular threshold. Both Miedema (Groothuis-Oudshoorn et al., 2006) and Schultz (1978) applied these thresholds and named those reporting annoyance greater than or equal to 72% "percent highly annoyed" (%*HA*). Shultz explained this choice over mean or median considering a few arguments.

The response is less scattered and the effect of non-acoustical factors on annoyance is reduced. It is argued (Schultz, 1978) that "highly annoyed" are proportion of people who can hear stronger outdoor noise and therefore their answer can be clear, conscious, and definite. When simultaneous indoor and outdoor exposures are measured, huge difference 20-30 dB(A) between them can be observed (Figures). Because of indoor activities, there may be significantly reduced relationship between exposures. Schultz (1978) provides an example that correlation between exposure and annoyance in terms of indoor activity such as reading, listening to radio or television in Belgium was dropped from 0.87 with windows open to 0.44-0.52 with windows closed.

It is also argued by Schultz (1978) that median of responses is not dealing with problem at all. Median represents a proportion of people who usually express no complaints. Apart from aforementioned arguments, median is problematic to translate from one scale to another.

Similarly, Miedema introduced two additional thresholds: "percent little annoyed" (%*LA*)--those who report annoyance greater or equal to 28% and "percent moderately annoyed" (%*MA*)--those who report annoyance greater or equal to 50%. The percent equivalence corresponding to the particular level of annoyance is calculate from the formula (Miedema et al., 1998)

$$\%A = \frac{i - 1/2}{m} \times 100\% \tag{3.1}$$

The terms m, i, and $\%A$ correspond to a number of all categories in annoyance scale (m) and a category (i) for which a percentage equivalence ($\%A$) is computed. Each percentage for both five-point and eleven-point scales is included in Table 3.

In each regression model estimating relationship between independent variable and ordinal dependent variable, the boundary is an inseparable term involved in calculation. Figure 2, along with percentage representation of categories, illustrates all boundaries as dashed lines whereas categories are shown as solid lines. Categories fall between two adjacent boundaries as mid-points. Although detailed explanation is provided in one of the further chapters, the formula is presented here. The boundaries can be calculated while applying the formula (Groothuis-Oudshoorn et al., 2006)

$$B = \frac{i}{m} \times 100\% \tag{3.2}$$

Table 3. List of all category names and their percent equivalences

Category name	i	%A	Category name	i	%A
Not at all	1	10.0%	0	1	4.5%
Slightly	2	30.0%	1	2	13.6%
Moderately	3	50.0%	2	3	22.7%
Very	4	70.0%	3	4	31.8%
Extremely	5	90.0%	4	5	40.9%
			5	6	50.0%
			6	7	59.1%
			7	8	68.2%
			8	9	77.3%
			9	10	86.4%
			10	11	95.5%

Similarly, m, i, and B represents a number of all boundaries (m) and a number of boundary (i) starting from 0 for which a percent equivalence (B) is calculated. A number of boundaries (m) is always equal to number of categories plus one. As can be noticed, categories are mid-points between two adjacent boundaries.

It is worth noticing that in both annoyance scales each category cannot precisely meet thresholds (See Figure 2)--50% is the exception only if an annoyance scale is expressed by odd number of categories. The grouped regression model overcomes this issue by grouping and summarizing annoyance into whole scale assuming boundaries along with categories equally scattered along the population. This model, however, was not used to analyse exposure-response relationship. Ordinal probit models calculate proportion between probabilities. Therefore, percent little, moderately, and highly annoyed cannot be expressed utilizing Miedema's approach. Therefore, by applying a cumulative alternative, it was possible to express three category of annoyance, in similar way to Miedema's model. In 5-point semantic scale, reporting annoyance higher than:

- category 1 corresponds to percent little annoyed

- category 2 corresponds to percent moderately annoyed
- category 3 corresponds to percent highly annoyed.

On the other hand, in 11-point numeric scale, reporting annoyance higher than:

- category 2 corresponds to percent little annoyed
- category 5 corresponds to percent moderately annoyed
- category 8 corresponds to percent highly annoyed.

3.3. EARLIER MODEL OF EXPOSURE-RESPONSE RELATIONSHIP

Schultz (1978) in his work explained synthesis of exposure-response relationships. This paper is regarded as seminal work in this field. Shultz collected data from eleven studies of social surveys and then converted each annoyance scale to its percentile-base metric. This approach was required because of variations between each annoyance scales applied in analysis. The studies were collected from different countries and cultures. Annoyance in each study was assessed by different scales. Therefore, Shultz decided to translate each semantic scale into a corresponding numeric scale which eased to process them mathematically. Then, the percentile metric was used to describe a proportion of participants who reported upper part of annoyance scale. Specifically, Shultz applied the percentile equal to seventy two in annoyance scale and called all the participants who reported this or higher annoyance degree as “percent highly annoyed”-- the term is also denoted as *%HA* in literature (Fidell et al., 1989; Groothuis-Oudshoorn et al., 2006; Miedema et al., 1998; Miedema et al., 2001). Shultz’s study revealed an inevitable influence of the other non-acoustical factors on annoyance. It was found that analysis of higher annoyance degrees reduced effects of such factors considering individuals and groups.

The summary of all data points drawn by Schultz (1978) is illustrated by Figure 3. Exposure is measured by L_{dn} (See section 4.5.1). This is one of the first metrics to express the exposure-response relationship; this metric was then extended to L_{den} (See section 4.5.1). Shultz expressed this relationship as a third-order polynomial fit curve. The data points correspond to “percent highly annoyed”.

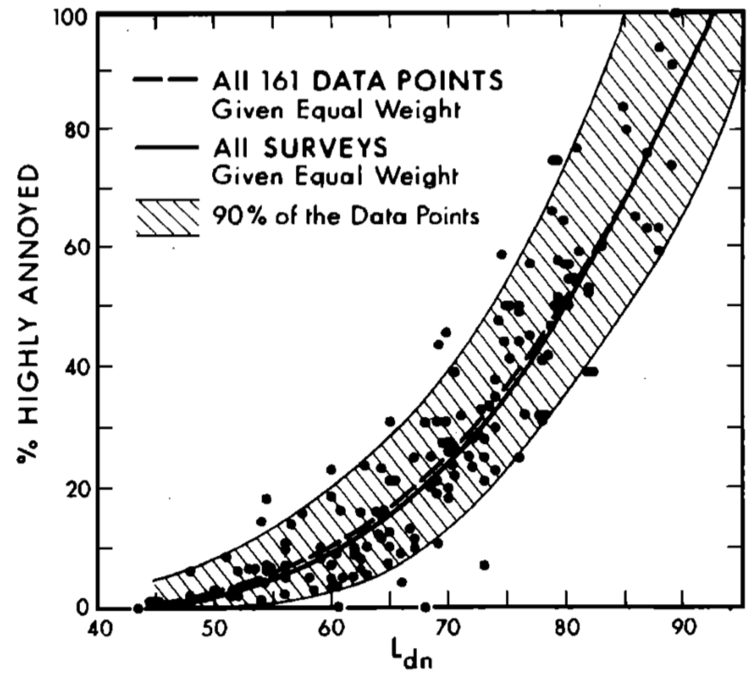


Figure 3. Summary of all survey data points Schultz (1978). The curves are expressed as the third-order polynomial fit.

Figure 3 confirms that annoyance increases with exposure rates and its relationship was not found to be linear. Although confirmed by Fidell et al. (1989) who also included an additional 292 data points to Shultz's original dataset in such curve, polynomial fit is rather a questioned technique to express exposure-response relationship. A note of importance is that annoyance curves shown by Figure 3 are the result of a synthesis of different transportation modes--this was, however, the subject of a criticism by Kryter (1982). Further studies revealed a separate analysis of different transportation modes (Miedema, 2007).

3.4. POLYNOMIAL FIT

The third-order polynomial fit regression seemed to work for Shultz. The data revealed an expected trend that annoyance increases with exposure rates. In this subsection, it is shown that polynomial fit may not work for some data set and consequently statistical methods along with monotonic functions were considered, instead.

3.4.1. Linear regression

Linear regression, a first-order polynomial fit, is the one of many approaches to find estimates to express exposure-response relationships. The linear regression model are expressed as followed

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \tag{3.3}$$

where **y** is the dependent variable--a column vector of *N* observations, the **X** is the independent variable--a matrix *N* x *K*, where *K* corresponds to a number of predictors, **β** is a column vector of a number of coefficients equal to a number of predictors, and **ε** is the stochastic error--a column vector of the same dimensions as the dependent variable **y**. The first-order polynomial fit imposes a number of assumptions which must not be violated. If these assumptions are violated, Ordinary Least Square (OLS) estimator of **β** is inefficient and the standard errors are biased resulting in incorrect test statistics.

- Linearity – in equation (3.3), the independent variable **y** has to be linearly related to the **X** through **β**;
- Collinearity – **X** is of full rank meaning none of the $\mathbf{x}_k$ (a *K*th column of the vector of **X**) is a linear combination of the remaining vectors in **X**;
- Zero conditional mean – expected value of error $\boldsymbol{\varepsilon}_i$ given $\mathbf{x}_i$ (an *i*th observation) is equal to 0. This assumption implies that the conditional expectation error given **x** is a linear combination of *x*'s:

  $$E(y_i \mid \mathbf{x}_i) = E(\mathbf{x}_i\boldsymbol{\beta} + \varepsilon_i \mid \mathbf{x}_i) = E(\mathbf{x}_i\boldsymbol{\beta}) + E(\varepsilon_i \mid \mathbf{x}_i) = \mathbf{x}_i\boldsymbol{\beta} + 0 = \mathbf{x}_i\boldsymbol{\beta}$$

- Homoscedastic and uncorrelated errors – the errors have a constant variance for given **x** (See Figure 4); Heteroscedastic errors, on the other hand, are characterised by different variance for each observation;
- Normality – when errors are the result of combined effects of many small factors, it is reasonable to assume that they are normally distributed

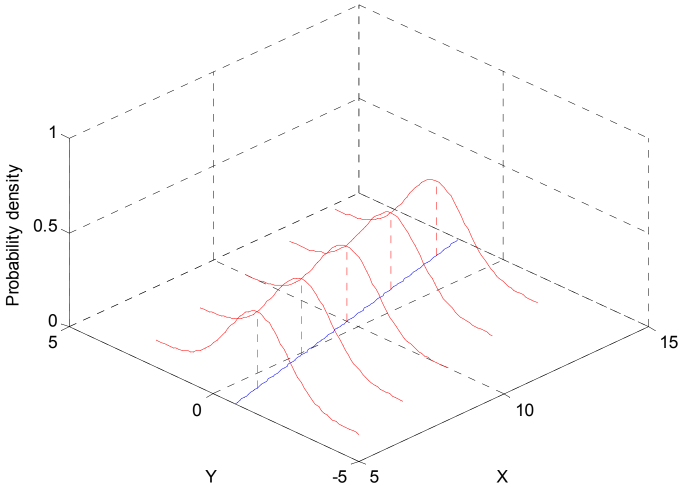


Figure 4. Linear regression model with distribution of **y** given **x**. The red curves show the error distribution around the E(**y**|**x**) with constant variance; this is required in order for OLS to produce efficient and unbiased results.

The example of linear regression fit is presented by the first figure in the Table 4 (the upper left-hand side figure). The left hand-side upper figure shows a bar graph, the curve comprised by red dots, and a straight line comprised of blue dots. The bar graph illustrates proportion or group of respondents in each noise exposure category. It shows that 65 dB(A) contains highest proportion of respondents. From this graph, it can be seen that the exposure-response relationship is not linear. As such, the first assumption is already violated causing this method invalid to apply.

3.4.2. Higher-order polynomial fit

Schultz (1978) applied the third-order polynomial fit in his work (See Figure 3). However, the polynomial method may not be a correct approach for problems regarding social-acoustics surveys. Apart from linearity, the polynomial curves share limitations due to the same assumptions imposed on linear regression. For this method, OLS estimator is also inefficient and results with incorrect estimates due to biased standard error. Additionally, polynomial curves may or may not monotonically change. It is said to be an expected feature in analyses of exposure-response relationships (see figures in the) (Agresti, 2002). It is also likely that polynomial fit curves would cross minimum “0” or maximum “1” in probability when estimation is extended. The normal cumulative distribution and logistic cumulative probability functions overcome these problems (green marks shown by the lower right-hand side graph in the Table 4).

Figure 8, for instance, illustrates a normal cumulative distribution function that is monotonically increasing. It also varies between probabilities “0” at -∞ and “1” at +∞ of exposure. Consequently, normal cumulative distribution function is commonly used to express exposure-response relationships because it overcomes aforementioned problems. Logistic cumulative probability function also commonly applied in studies has a similar shape to a normal distribution but the variance is greater from standard normal distribution by about $\pi/\sqrt{3} \approx 1.81$ (Long, 1997)

$$\Lambda(\mathbf{y} \mid \mathbf{x}) = \frac{e^{\boldsymbol{\beta}\mathbf{x}}}{1+e^{\boldsymbol{\beta}\mathbf{x}}} \tag{3.4}$$

3.4.3. Linear regression for binary response

The linear regression is also invalid for data set whose categorical dependent variable is binomial or ordinal when more than two categories are applied. Formula for a linear regression model applied for binary dependent variable has the same form

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

The term **X** is a matrix containing column vectors of observations, $\boldsymbol{\beta}$ is a column vector of parameters and $\boldsymbol{\varepsilon}$ is an error term. Binary response dependent variable **y** is a particular case of categorical dependent variable. However, when more than two categories are considered, then categorical variable is ordinal. In binary regression model (BRM), y_i can take only two categories. The first of the figures in the Table 4 illustrates linear changes in probability.

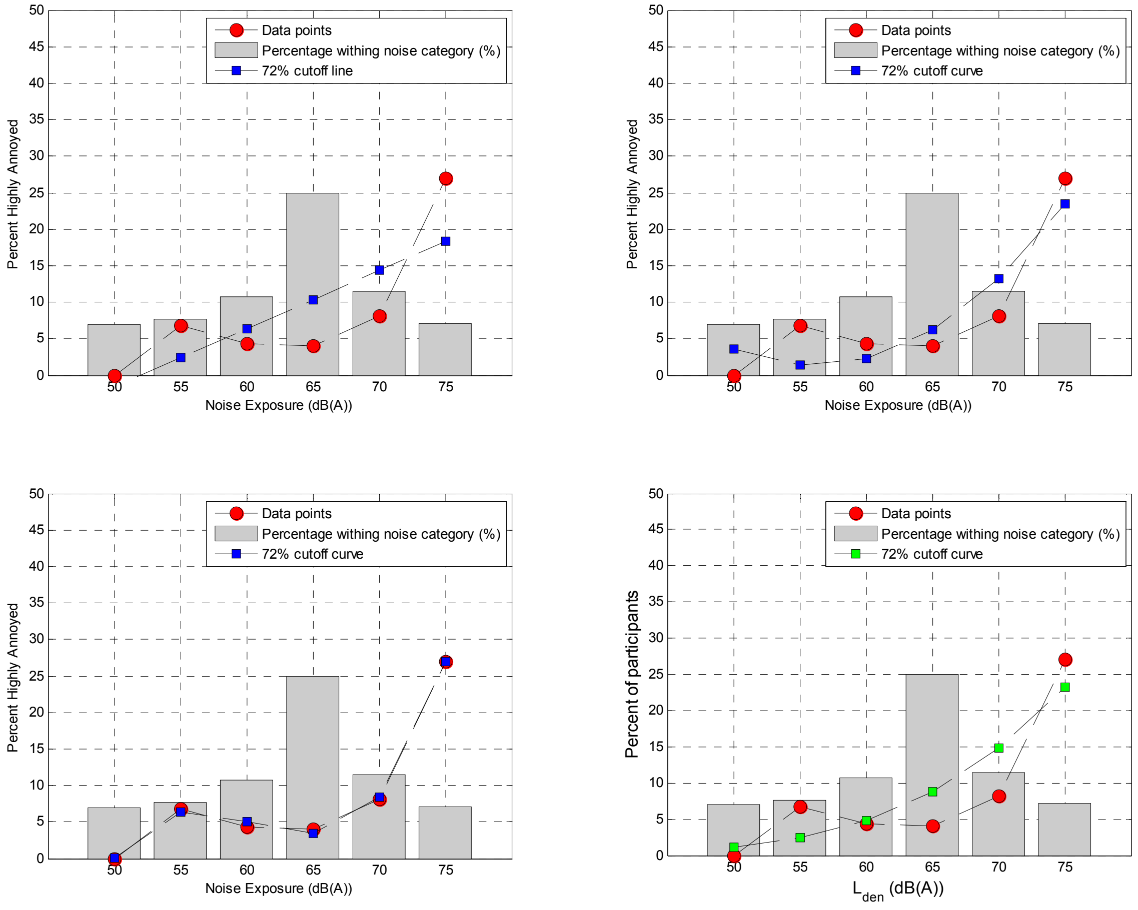
The purpose of the following derivation is to confirm that linear regression models do not work for categorical data. Long (1997) and Agresti (2002) provide the more solid proof. For the regression model, the expected value $E(y_i|\mathbf{x}_i)$ is equal to

$$E(y_i \mid \mathbf{x}_i) = 1 \times \Pr(y_i = 1) + 0 \times \Pr(y_i = 0) = \Pr(y_i = 1)$$
$$E(y_i \mid \mathbf{x}_i) = \mathbf{x}_i\boldsymbol{\beta}$$

Therefore

$$\Pr(y_i = 1) = \mathbf{x}_i\boldsymbol{\beta}$$

Table 4. The first three figures (clockwise from top left) illustrate the first, the second, and the third order polynomial fit of highly annoyed (*%HA*). The fourth figure illustrates application of the fit by normal cumulative distribution function.



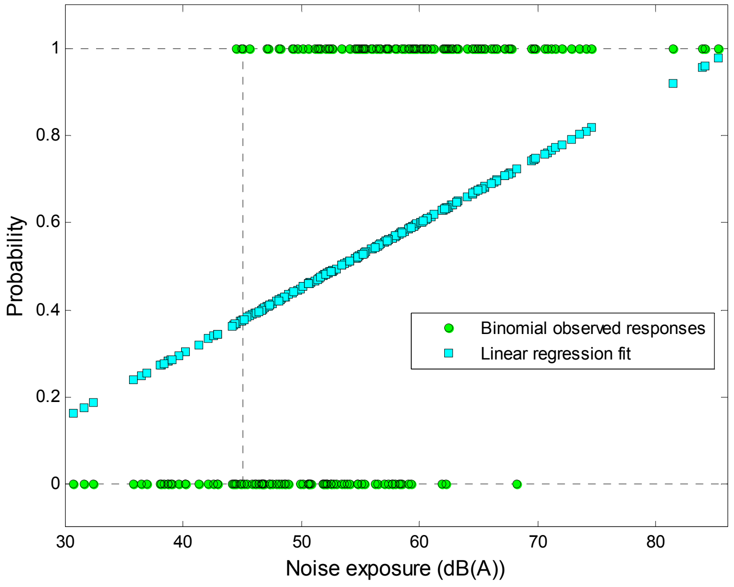


Figure 5. Linear probability model. Categorical dependent variable is of a binary response. A line comprised of light blue marks represent an expectation E(**y**|**x**) of linear regression model whereas observed data are shown as green marks.

Section (3.4.1) lists assumptions imposed when linear regression is applied. In terms of binary dependent variable, assumptions such as constant variance and normal distribution of error are violated. Variance of a random variable having binomial distribution can be calculated from the equation

$$Var = \mu(1-\mu)$$

The term μ denotes mean. Similarly, variance of regression model of **y** given **x**, where the expectation is equal to **xβ**, varies according to the equation

$$Var(y\,|\,\mathbf{x}) = \mathbf{x\beta}(1-\mathbf{x\beta})$$

This implies that variance of errors depends on **x** and is not constant. Due to this problem, OLS predictor is therefore invalid resulting in biased and incorrect estimates.

Long (1997) also listed two other problems regarding linear regression of binary variable. In linear regression model, errors are not normally distributed. Figure 5 shows observed (green marks) and fitted by LRM data (light blue marks). The errors **ε** are equal to the difference between observed and fitted points--in Figure 5, this is visualized by the distance along the vertical dotted line from one of the fitted points to the corresponding observed point:

$$\begin{aligned} \varepsilon_0 &= 0 - \Pr(y=0) \\ \varepsilon_1 &= 1 - \Pr(y=1) \end{aligned} \qquad (3.5)$$

Errors show a pattern indicating dependency on *x*. Figure 6 shows residuals from linear regression model applied to binary categorical dependent variable. The distribution contains two peaks because errors are related to variable *x*. Considering both categories “0” and “1” in Figure 5, in this particular case, lots of points are concentrated around the value of 50 dB(A) at the category “0”, and 60 dB(A) at the category “1”. The same point concentration is shown by the histogram and scatter plot in Figure 6. For a comparison, normally distributed errors are shown in Figure 11. This figure illustrates the distribution of residuals corresponding to a binary regression model in Figure 9 (red marks) whose parameters have been estimated based on the same data set as for linear regression from Figure 5.

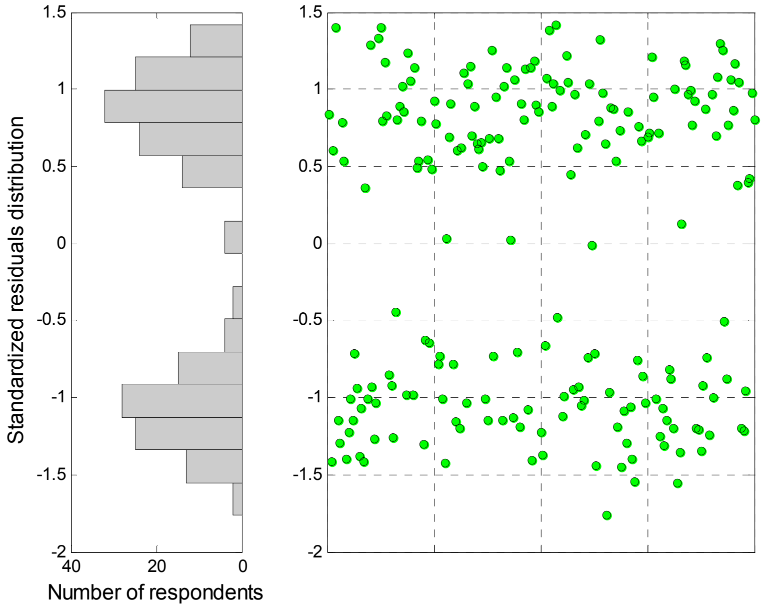


Figure 6. Distribution of residuals from linear regression model with binary dependent variable.

The remaining problem discussed by Long (1997) refers to linear changes in probability which is unrealistic. A unit increase in x_k results in a constant change of β_k in the probability holding all other variables constant. This can be explained by example with regard to noise exposure and annoyance; Figure 9 shows the graph similar to Figure 5 with additional data points forming output from the binary regression model (BRM). The probability distribution is cumulative. Its shape forms so-called *S*-curve. Analysis of the cumulative probability distribution reveals that at very low level of noise exposure, annoyance may be near zero and therefore changes in noise level such as 35 dB(A) to 45 dB(A) would result in very little increase in probability. Much greater increase can be expected when noise level changes from 50 dB(A) to 60 dB(A). The slope of the S-curve given 50 or 60 dB(A) of noise level is much greater. Finally, at very high level of noise, the probability is expected to be very high because the nearly all the probability is included at this level of noise. Consequently, the large increase in noise level from let's say 70 dB(A) to 85 dB(A) would only result in little increase in annoyance. Also, the slope of the S-curve is much lower indicating little changes in probability.

Figure 11 shows distribution of residuals from the binary regression model whose parameters were estimated using the same data set as for estimating parameters for linear regression model (See Figure 5 and Figure 6). In Figure 6, the distribution of errors is much closer to normal.

3.5. REGRESSION MODELS FOR ORDINAL RESPONSE VARIABLES

The previous section provides an explanation on issues when linear regression is applied. A couple of problems have been indicated with the consequences on accuracy when Linear Regression Models are applied. This section provides an explanation of Ordinal Regression Models (ORM). The name stems from application of an ordinal dependent variable (DV).

3.5.1. Binary Regression Model

The Binary Regression Model (BRM) takes place when a DV (or response variable) has only two outcomes: true or false. The DV is coded as "0" or "1"; the numbers correspond to false and true, respectively. BRM applies a probability distribution of DV and utilizes it to find probability that dependent, an observed, variable has outcome equal "1". The term *true* may be interpreted as e.g. being annoyed or having a chance to obtain a job. An independent variable (IV) may express a level of exposure or number of children in family. By means of the binary regression model, a relationship between independent and dependent variables can be estimated. Although a full description of BRM models is out of the scope of this work, a short explanation is provided to illustrate the process of the model development. More detailed information on this topic are presented by Long (1997) and Agresti (2002).

Latent variable

One of the a few approaches towards developing relation of DV to IV is based on latent variable *A*. (See Figure 7). As Latent variable *A* is not observed, their values are unknown. It is assumed that *A* changes from -∞ to +∞. The latent variable can be mapped onto an observed variable, though. If *A* is lower than a certain value, then DV *y* takes the category "0" or false. Similarly, if the latent variable *A* is higher than a certain value, then observed variable takes the category "1". Whether *A* is greater or less than a certain value is determined by a threshold τ. The formula below shows this relationship

$$y = \begin{cases} 0, \text{ if A} \le \tau \\ 1, \text{ if A} > \tau \end{cases} \tag{3.6}$$

Figure 7 illustrates determination of probability that DV is equal "1". Horizontal axes correspond to some exposure changes and a response given these exposures. The vertical axis shows probability distribution of errors around a mean of DV given x. In this particular case, a normal distribution is assumed but different probability functions such as logistic may also be considered. Each green area shows probability that DV is of category "1" given x. Due to the constant threshold τ, indicated by a blue dashed line, this area changes with exposure rates. The red solid line is the expectation $\mathrm{E}(y|x)$. Any value of the latent variable (A) greater than the threshold τ corresponds to observed variable equal to "1" and vice versa, according to the equation (3.6).

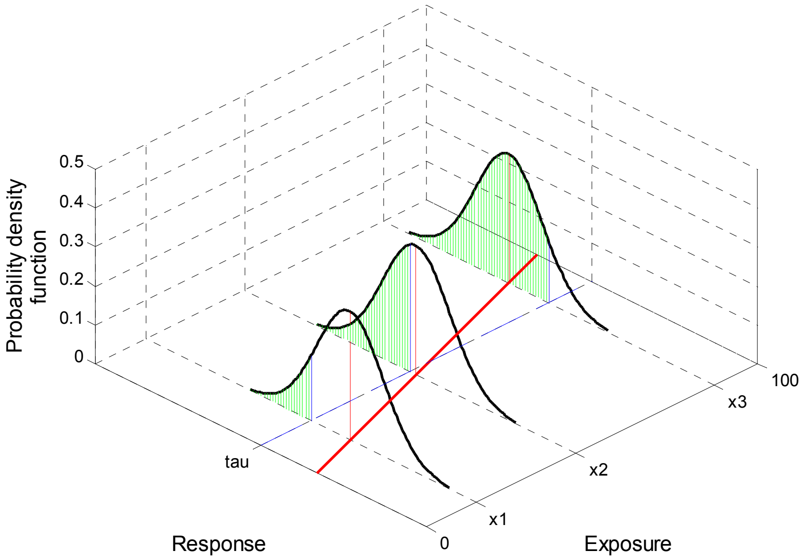


Figure 7. Probability distribution of A given x for BRM.

The meaning of the latent variable A can be explained via illustrating the distance of the response given x to probability equal to one. In terms of observed responses, probability that y is of category "1" (or true) given x increases with rates of x. Figure 7 and Figure 8 illustrate this point of view by showing the green shaded area (Figure 7) or the cumulative function in (Figure 8) for three arbitrary values $x1$, $x2$, and $x3$. The probability that y is of category "1" increases because the green area increases. More over than that, the response given $x3$ is observed at the green shaded portion of error in Figure 7--the probability of reporting category "1". Even if the expected value is in this region, it is still possible to observe a category "0" because it represents the probability which depends on error distribution.

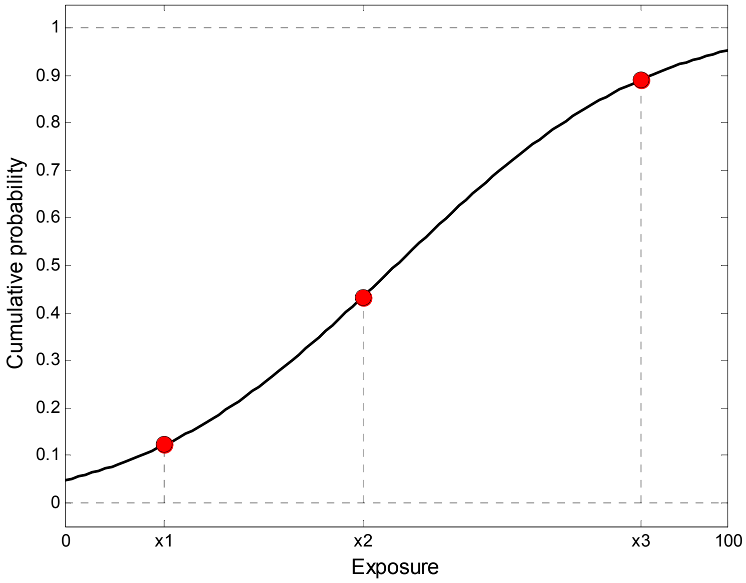


Figure 8. Cumulative distribution of *A* given *x*.

Development of the model

At this point, derivation of the fundamental formulas should be a straight forward step. By assuming a specific form of distribution, it is possible to compute the probability of *y* = 1 for given **x** (Figure 7). The probability that $A > \tau$ is

$$\Pr(y = 1 \mid \mathbf{x}) = \Pr(A > \tau \mid \mathbf{x}) \tag{3.7}$$

Because $A = x\beta + \varepsilon$, it follows that

$$\begin{aligned}\Pr(y=1\mid\mathbf{x}) &= \Pr(A>\tau\mid\mathbf{x})\\ &= \Pr(-A\le-\tau\mid\mathbf{x})\\ &= \Pr(-x\beta-\varepsilon\le-\tau\mid\mathbf{x})\\ &= \Pr(\varepsilon\le\tau-x\beta\mid\mathbf{x})\end{aligned}$$

This is the cumulative distribution function of the error evaluated at $\mathbf{x\beta}$. A more general form is following

$$\Pr(y=1) = F(\tau - \mathbf{x\beta}) \tag{3.8}$$

The equation (3.8) expresses probability that dependent variable *y* is equal “1”. The general term *F*(.) corresponds to cdf’s (cumulative distribution function) of any form. It is usually assumed that *F*(.) represents a normal or a logistic distribution depending on which distribution is more accurate. All examples along with explanation assumed the cumulative normal distribution function. Also, it is reasonable to assume a normal distribution of errors in any of studies regarding social surveys. The slight or moderate influence of other factors not involved in analysis causes the errors to become normal in large sample size Long (1997). Therefore, in this study, errors are assumed to be normal.

Due to nonlinearity between exposure and response, parameters for the regression model can only be estimated via maximum likelihood function. This function is explained in the next section, along with development of the Ordinal Regression Models.

As an example, Figure 9 illustrates the relationship between randomly generated values of noise exposure and binomial response. As can be seen, green points (an observed response) can only take categories “0” or “1”. The concentration of category “0” is at lower rates of noise exposure, whereas category “1” is more often observed at higher range of noise level. The light blue line corresponds to simple linear regression which, as explained, does not provide correct estimation.

Figure 10 illustrates data from which regression was estimated. In this figure, green marks are observations. The percentage scale refers to position of a category with respect to its position on an ordinal scale. Percentile values are equally placed because of the assumption that each interval between two adjacent category levels is equal. This is only true when response variable is ordinal. Otherwise, the percentage scale is meaningless--when a response variable is nominal. The annoyance degrees were calculated from the equation (3.1). Percentage scale allows comparing this study with the others. The threshold is set to fifty percentile point between both categories.

Figure 11 shows the residual distribution. Comparing the residual distribution shown by Figure 6 with the residual distribution in Figure 11, it can be seen that residuals from BRM are much closer to normal distribution.

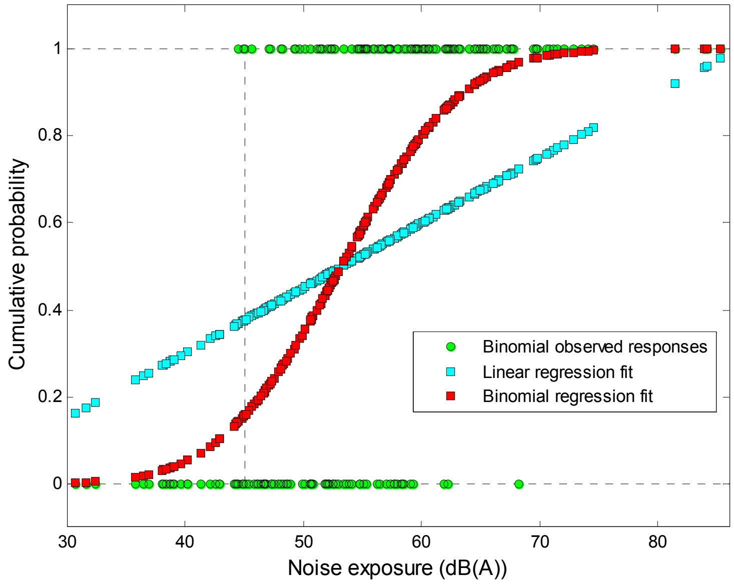


Figure 9. Linear probability model. Categorical dependent variable is of a binary response. Light blue marks represent an expectation E(**y**|**x**) of linear regression model, red marks represent binary regression model, and observed data are shown as green marks.

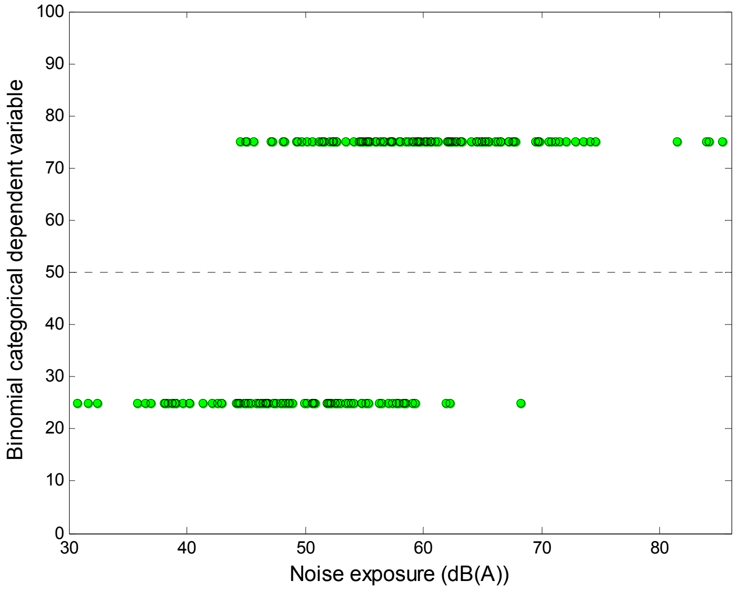


Figure 10. Distribution of binary response variable; annoyance degrees are expressed in a percentage scale, according to section (3.2).

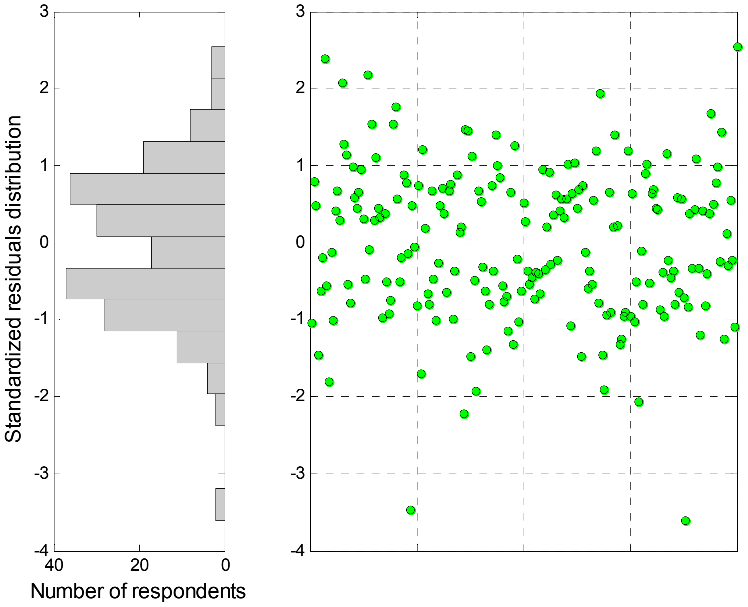


Figure 11. Distribution of residuals from the binary regression model.

3.5.2. Ordinal Regression Models

Ordinal Regression Model (ORM) is a simple extension of BRM. Long (1997) provides explanation and derivation of formulas based on latent variable. It also offers a short discussion on different approaches focusing on deriving key formulas for ordinal regression models. The derivations are based on utilizing latent variables or logits[6]. The second approach is also used in the book of Agresti (2002) where explanation of Generalized Linear Models is provided. The full explanation of these two approaches is also out of the scope if this work.

An ORM utilizes ordinal response variable with more than two categories. According to theory, categories corresponding to annoyance levels are the midpoints between thresholds separating each category.

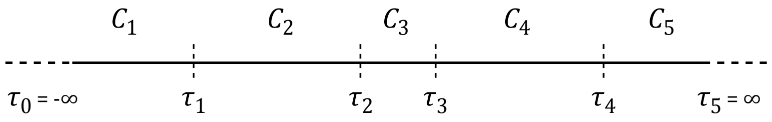


Figure 12. The general visualization of an ordinal response variable with thresholds separating particular category levels.

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[6] Logit is a natural logarithm of an odds ratio calculated from probability of two categories

Development of the model

Apart from number of categories, all other rules regarding ORM remain the same. However, due to greater number of categories, a latent variable does not express probability that a category is under or above a threshold but between two thresholds representing boundaries (See section 3.2). Therefore, derivation can be started from a similar equation to (3.7) taking the form as below

$$\begin{aligned}\Pr(y_i = m \,|\, \mathbf{x}_i) &= \Pr(\tau_{m-1} \le A_i < \tau_m \,|\, \mathbf{x}_i) \\ &= \Pr(\tau_{m-1} \le \mathbf{x}_i\boldsymbol{\beta} + \varepsilon_i < \tau_{m-1} \,|\, \mathbf{x}_i) \\ &= \Pr(\tau_{m-1} - \mathbf{x}_i\boldsymbol{\beta} \le \varepsilon_i < \tau_{m-1} - \mathbf{x}_i\boldsymbol{\beta} \,|\, \mathbf{x}_i) \\ &= \Pr(\varepsilon_i < \tau_m - \mathbf{x}_i\boldsymbol{\beta} \,|\, \mathbf{x}_i) - \Pr(\varepsilon_i \le \tau_{m-1} - \mathbf{x}_i\boldsymbol{\beta} \,|\, \mathbf{x}_i) \\ &= F(\tau_m - \mathbf{x}_i\boldsymbol{\beta}) - F(\tau_{m-1} - \mathbf{x}_i\boldsymbol{\beta})\end{aligned} \qquad (3.9)$$

The term *m* corresponds to a number of a category starting from 1. The probability that a random variable is between two categories is expressed by last row in equation (3.9). This is a general from because *F*(.) can be of either normal, or logistic, or any other distribution, although the form of a distribution depends on distribution of the error $\boldsymbol{\varepsilon}_i$ around a mean. Considering two particular cases when $\tau_0 = -\infty$ and $\tau_m = \infty$, as well as assuming normal distribution of the errors, equation (3.9) takes the following form for each category

$$\Pr(y_i = m \,|\, \mathbf{x}_i) = \begin{cases} \text{if } m = 1, & \Phi(\tau_1 - \mathbf{x}_i\boldsymbol{\beta}) \\ \text{if } m = 2 \ldots, & \Phi(\tau_m - \mathbf{x}_i\boldsymbol{\beta}) - \Phi(\tau_{m-1} - \mathbf{x}_i\boldsymbol{\beta}) \\ \text{if } m = \max, & 1 - \Phi(\tau_{m-1} - \mathbf{x}_i\boldsymbol{\beta}) \end{cases} \qquad (3.10)$$

An illustration of the equation (3.10) is shown by Figure 13 and Figure 14. Figure 13 shows an example of probability of annoyance of category $m = 1$, between thresholds τ_1, and τ_2. For three arbitrary exposure levels x_1, x_2, and x_3, Figure 13 and Figure 14 show the probabilities in terms of green area and green lines, respectively. The area changes when exposure increases, so does length of green lines. As can be seen, the highest probability that $m = 1$ is for the lowest exposure x_1--the green area is the largest. Consequently, increases of exposures causes decreases of this area and therefore decreases in probability that annoyance is within the same category $m = 1$. This particular cases corresponds to second condition of the equation (3.10).

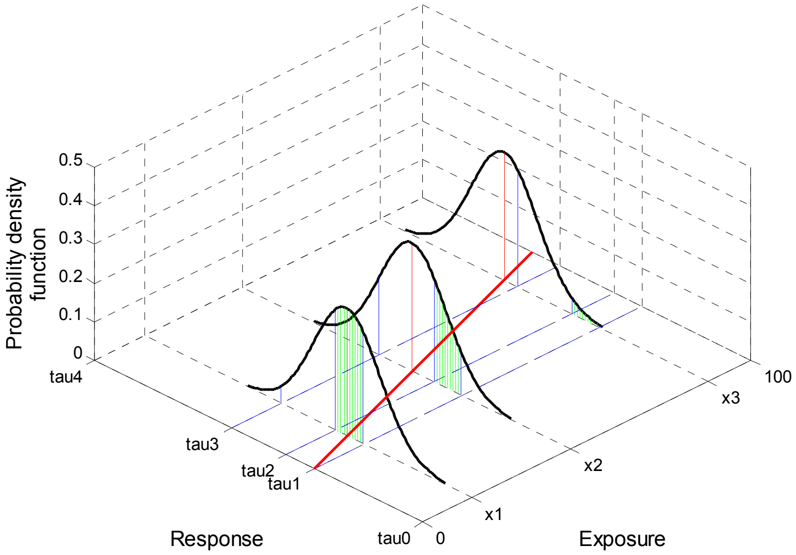

Figure 13. Probability distribution of latent variable *A* given **x** for ORM.

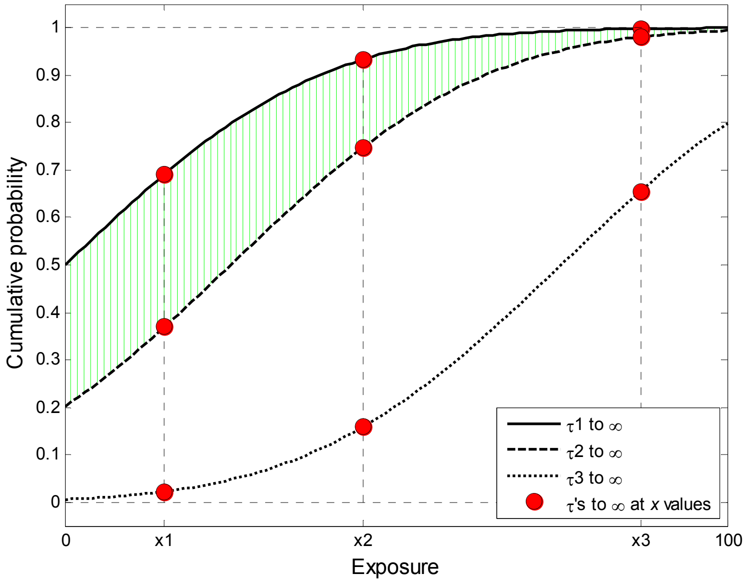

Figure 14. Cumulative distribution of latent variable *A* given **x** for ORM. The green area illustrates changes of probability that a response is of category m=1 (between thresholds τ_1 and τ_2)

A common way of presenting exposure-response relationship is to draw a cumulative probability curve. Such curves include responses associated with not only one category but all above a certain thresholds. In Figure 13, this corresponds to the area under the normal distribution starting from one of the thresholds, for instance τ_1 up to $+\infty$. Therefore, the cumulative probability in Figure 14 shows that probability increases with the increase in the exposure. Additionally, the lower the threshold τ_m, the highest is the probability for the same x_k, simply because the area under the normal distribution is larger. Figure 14 shows three annoyance curves considering three thresholds and three different levels of exposure. Annoyance between the threshold τ_1 and +∞ in Figure 13 is represented by the solid line in Figure 14. For exposure x_3, the cumulative probability that the response is greater than the threshold τ_1 is almost one because this particular situation corresponds to the almost whole area in Figure 13 between τ_1 and +∞.

3.5.3. Estimation of the model parameters

Similar to linear regression, parameters of binary regression or ordinal regression models have to be estimated. Unlikely for linear regression, set of linear equations cannot be applied, for the model is non-linear and estimation would provide incorrect estimation due to biased standard error. Therefore, both models are estimated via maximum-likelihood function (MLF). It is out of the scope to provide full explanation of this approach. Nonetheless, for given data in **X**, it is to find best set of parameters, for instance mean and standard deviation, which maximizes this function. This process involves an assumption that the data are actually of a particular distribution. When the MLF takes the same form, parameters are estimated via mathematical analysis finding first and second derivatives. Because the likelihood function is usually concave, the process is to find maximum of the MLF.

For ORM, MLF takes the same form as equation(3.10)

$$L(\boldsymbol{\beta},\boldsymbol{\tau}\,|\,\mathbf{X})=\prod_{i}^{n}\prod_{y=j}\left[\Phi(\tau_j-\mathbf{x}_i\boldsymbol{\beta})\Phi(\tau_{j-1}-\mathbf{x}_i\boldsymbol{\beta})\right] \qquad (3.11)$$

The expression y = j indicates that for this particular likelihood function (LF) only responses corresponding to particular observation are taken into account. If covariate matrix $\boldsymbol{\Sigma}_b$ of beta coefficients $\boldsymbol{\beta}$ is known, 95% confidence intervals for each observation i can be estimated from the equation

$$C_{i,LU}=\mathbf{x}_i\mathbf{b}-Z\sqrt{\mathbf{x}_i^{'}\boldsymbol{\Sigma}_b\mathbf{x}_i} \qquad (3.12)$$

The term **x** is the column-like vector of observations including a vector of ones at the first position. $\boldsymbol{\Sigma}_b$ is a covariate matrix of β coefficients and constant Z depends on which confidence interval is to be estimated. For normal distribution, 95% confidence interval corresponds to value Z equal to 1.96. Confidence intervals are finally calculated from equation

$$1-\Phi\left(\frac{C-C_{i,L,U}}{s}\right) \tag{3.13}$$

3.6. GOODNESS-OF-FIT

Goodness-of-fit is an important measure of how accurately an output from regression model is produced. In general, deviation is closely related to goodness-of-fit. Deviation is calculated from sum of squared differences between observed and estimated values

$$\text{deviation}=\sum(\text{observed-model})^2$$

Model sum of squares, denoted as SS_{M}, is the value which is obtained from calculation of differences between ordinary least square regression and mean. On the other hand, residual sum of squares SS_{R} is calculated from differences between the observed data and mean.

$$SS_R=\sum\left(y_i-\bar{y}\right)^2$$
$$SS_R=\sum\left(\hat{y}_i-\bar{y}\right)^2=SS_T-SS_R=\sum\left(y_i-\bar{y}\right)^2-\sum\left(y_i-\hat{y}\right)^2$$

For ordinary least square regression, the goodness-of-fit is generally assessed along all observation by calculating the proportion of model sum of squares and residual of sum squares.

$$R^2=\frac{SS_M}{SS_T}=\frac{SS_T-SS_R}{SS_T}=\frac{\sum\left(y_i-\bar{y}\right)^2-\sum\left(y_i-\hat{y}\right)^2}{\sum\left(y_i-\bar{y}\right)^2}$$

Hence, the formula takes the final form

$$R^2=1-\frac{\sum\left(y_i-\hat{y}\right)^2}{\sum\left(y_i-\bar{y}\right)^2} \tag{3.14}$$

R^2 varies between zero and one. If the model fits the data very well, then observation lie close to the regression line representing a mean or expected value. Therefore, the nominator is low and R^2 reaches high values close to unity. On the other hand, if observations are scattered around regression mean, then nominator is similar to denominator and consequently when R^2 is low, it means a model does not accurately predict observations. Unfortunately, unlike ordinary least squares regression, there is no universally accepted method of assessing the goodness-of-fit of a ordinal regression model, although many approaches have been proposed. Maximum likelihood function can be useful in comparing two models (Agresti, 2002; Long, 1997).

Two models differ in terms of number of predictors. The simplest model is the one which is described by the intercept term only. On the other hand, any other predictors included in the model decreases amount of remaining variation as well as deviation between data set and a model.

The model is thought to be saturated (Agresti, 2002) if all possible combination of covariates (predictors), including their interactions, are exhausted. Similar description of this problem is given by McFadden's. McFadden considers pseudo-R^2 to be estimated via likelihood function. The likelihood function of a full model (LL_{full}) is compared to the likelihood function of a model in which only the intercept term is considered ($LL_{\text{intercept}}$). L_{full} is considered to be analogous to the sum of squared errors. $LL_{\text{intercept}}$ is considered to be analogous to the total sum of squares

$$R^2 = 1 - \frac{LL(\text{model}_{\text{full}})}{LL(\text{model}_{\text{intercept}})} \tag{3.15}$$

R^2 is an important value which will be presented along with results obtained from logistic regression models.

3.7. ANALYSIS OF CATEGORICAL DATA VIA CONTINGENCY TABLES – ODDS RATIOS

3.7.1. Introduction

This section provides an outline of techniques considered when analysis of categorical data is conducted. The application of contingency tables along with *Odds Ratios* can be seen in the chapter regarding discussion of results (See section 5.3). It has been applied in this project because of categorical character of a dependent variable. This technique may be considered a complementary technique, yet giving important outcomes and supporting main results obtained from application of the ordinal probit model. Sleep disturbance is widely analysed via contingency tables and odds ratio. It has been confirmed that many non-acoustical variables are associated with sleep disturbance while controlled for noise exposure. For instance, the greater noise sensitivity, the increased is sleep disturbance.

Contingency tables can be used to compare groups on proportions of responses. *Odds Ratio* may appear as a parameter in models. Usually, tables are analysed for two categorical data. However, it is common to introduce the third variable *covariate* and analyse the model while two variables are controlled for the third one. Most of analysis involves contingency tables with binary variables. The other distributions such as Poisson and multinomial sampling are also possible (Agresti, 2002). With more than two category, variables in tables can be analysed in terms whether they are ordinal. Many outcomes become significant if this property is taken into account. Otherwise, contingency tables may show no association between variables when while ordinal character of variables is omitted.

The full explanation on contingency tables is out of the scope of this document. Only important statistics used in analysis are presented in this section along with terms required for understanding important parts. For a full and comprehensive explanation on this topic, the Reader is referred to the book by (Agresti, 2002).

3.7.2. Categorical variables and independence

Two categorical variables can show independence on each other. This can be analysed by comparing real counts in the cells with their expected values. If real values are equal or non-significantly different from to their expected values, then it is said that two variables are independent. The implication of such outcomes shows that variables are not associated; that is, changes of one variable (exposure) do not significantly influence on changes of the other variable (annoyance). The chapter regarding results (See Chapter 5) provides analysis of independence in terms of Pearson's (χ^2) and likelihood ratio (G^2) tests. This statistics simply compare each cell with corresponding expected value and provide a test whether variation is significant. When p value is greater than 0.05, it implies non-significant differences between expected and real values.

Table 5. Contingency tables with normal and expected frequencies

	Column		
Row	1	2	Total
1	π_{11} $(\pi_{1\|1})$	π_{12} $(\pi_{2\|1})$	π_{1+} (1.0)
2	π_{21} $(\pi_{1\|2})$	π_{22} $(\pi_{2\|2})$	π_{2+} (1.0)
Total	π_{+1}	π_{+2}	1.0

Table 6. Contingency tables with normal and expected frequencies

	Column		
Row	1	2	Total
1	n_{11} $(n_{1\|1})$	n_{12} $(n_{2\|1})$	n_{1+} (n)
2	n_{21} $(n_{1\|2})$	n_{22} $(n_{2\|2})$	n_{2+} (n)
Total	n_{+1}	n_{+2}	n

The contingency table is a joint distribution $[\pi_{ij}]$ of variables *X* and *Y*. All terms π_{ij} denote the probability variable represented by rows and variable represented by columns that occurs in the cell in *i* and column *j*. The *marginal distributions* are row and column totals that result from summing the join probabilities denoted by $[\pi_{i+}]$ for the row variable and $[\pi_{+j}]$ for the column variable. The character "+" denotes the sum over the index, as shown below

$$\pi_{i+} = \sum_j \pi_{ij} \text{ and } \pi_{+j} = \sum_i \pi_{ij} \tag{3.16}$$

The sum of each marginal distribution along either dimension gives 1.0.

Expected probabilities, on the other hand, can be computed from the formula

$$\pi_{ij} = \left(\pi_{i+}\pi_{+j}\right) / 1.0 \tag{3.17}$$

which is a product of two marginal probabilities divided by 1.0. The term "1.0" is important because the similar parameter may be calculated using counts in cells denoted by n_{ij}. For instance, $\pi_{ij} = n_{ij} /\mathrm{n}$ while *n* denotes the number of cases in analyses. Expected value $n_{ij} = n_{i+}n_{+j}/n$ etc. (See Table 6).

Two categorical variables are defined to be independent if all joint probabilities equal the product of their marginal probabilities. This term is important as it implies that two categorical variables are not associated between each other.

Terms in bracket denote conditional probabilities

$$\pi_{j|i} = \pi_{ij} / \pi_{i+} \tag{3.18}$$

3.7.3. Comparison of categorical variables

There are three different tests that are used to investigate the way two variables are related to one another: *Odds Ratios*, *Relative Risk*, and *Difference of Proportions*.

Difference of Proportions

For the cell in row *i* of an independent variable and column 1 of a dependent variable, $\pi_{1|i}$ denotes the conditional probability of response "1" given *i*. Similar to $\pi_{1|i}$, $\pi_{2|i}$ denotes the conditional probability of response "2" given *i*. Consequently, *Difference of Proportions* of category "1" and "2" given *i* is defined as difference between conditional probabilities $\pi_{2|i} - \pi_{1|i}$ given *i*. The response is statistically independent if $\pi_{2|i} - \pi_{1|i} = 0$.

Relative Risk

Difference of Proportions has a disadvantage when two groups are compared when their probabilities are roughly in the middle. For instance, comparing 0.401 and 0.410 gives difference of proportions equal 0.009, usually considered as not important. For groups when their probabilities reach the extreme values, e.g. .010 and 0.001, difference of proportion neglects its importance giving the same outcome 0.009. Such probabilities usually reflect a risk in terms of life or health. Therefore, very little changes in probabilities equal 0 or 1 may still become very important. As such, the ratio of proportions is therefore more informative. *Relative Risk* is denoted as

$$RR = \pi_{j|i_1} / \pi_{j|i_2} = \frac{\pi_{i_1 j} / \pi_{i_1 +}}{\pi_{i_2 j} / \pi_{i_2 +}} \tag{3.19}$$

Probability $\pi_{j|i1}$ and $\pi_{j|i2}$ are conditional probabilities of Y given i_1 and i_2. Relative risk of 1.0 corresponds to independence. For probabilities presented above, the relative risks are equal as follows: RR_1 = 0.010/0.001 = 10 while RR_2 = 0.410/0.401 = 1.02. As can be seen, RR_1 reflects 10 times greater probability of occurrence of the first category of Y given the first category of X (RR_1) with relation to the second category of X.

Odds Ratio

For two probabilities π_{11} and π_{12}, the *odds* are defined to be

$$\Omega = \pi_{11} / \pi_{12} \tag{3.20}$$

The *odds* are nonnegative. If $\Omega > 1.0$, then a category 1 of Y and category 1 of X are more likely to occur then category 2 of Y at category 1 of X. When $\pi_{i1} = 0.8$ and $\pi_{i2} = 0.2$, then $\Omega = 4$; a category "1" of Y given category i of X is four times as likely as category "2" of Y given category i of X. On the other hand, when $\Omega = 1/4$, then category "2" is four times more likely occur as likely as category "1" given category i. The ratio of two odds Ω_1 and Ω_2 in two rows is defined

$$\theta = \frac{\Omega_1}{\Omega_2} = \frac{\pi_{i_1 1} / \pi_{i_1 2}}{\pi_{i_2 1} / \pi_{i_2 2}} = \frac{\pi_{i_1 1}\pi_{i_2 2}}{\pi_{i_2 1}\pi_{i_1 2}} \tag{3.21}$$

and called *odds ratio*. The alternative name for θ is the *cross-product ratio*. When Ω_1 and Ω_2 are equal given binary variables, then variables X and Y are independent and $\theta = 1$. Values farther from one represent stronger association.

3.7.4. Partial association in tables

An important part of most studies is to conduct analysis with the choice of a control variable. When an effect of X on Y is studied, it is noteworthy to consider control of any covariate which influences on relationship between X and Y. This involves analysis where covariate is held at its constant. Sometimes, an observed effect of X on Y may reflect an effect of a covariate on both X and Y. The relationship between X and Y is then *confounding*. The analysis is controlled for the third variable, let's say Z, by studying the relationship between X and Y at fixed level of variable Z. These cross sections are called *partial tables* (Agresti, 2002).

The chapter 5 contains a couple of analysis that apply this technique to observe changes under or without the influence of a covariate. In the work presented by this Thesis, a variable that other variables are controlled for is the noise exposure L_{den}. Each sub-table which contains cells for particular noise category (e.g. 40-50, 50-60, or 60-70 dB(A)) is called *partial table*. In contingency tables the last row “Total” is obtained by summing all counts from cells for each partial table. The table obtained by the latter operation is called *marginal table*. The outcomes from marginal tables are also compared with outcomes from partial tables to investigate relationship of two variables under or without the influence of a covariate (noise exposure). A couple of example regarding confounding outcomes are discussed by (Agresti, 2002).

Because the results from contingency tables are based on analysis from partial and a marginal table, it is important to indicate a slight difference in formula (3.21). For simple contingency tables where a third variable is not involved, formula (3.21) is true. However, in terms of partial tables, formula (3.21) is applied either to each partial or marginal tables. Therefore, terms in this equation should simply have an additional index referring to which category K of the third variable is this formula applied for

$$\theta_{(K)} = \frac{\Omega_{1(K)}}{\Omega_{2(K)}} = \frac{\pi_{i_1 1,(K)} / \pi_{i_1 2,(K)}}{\pi_{i_2 1,(K)} / \pi_{i_2 2,(K)}} = \frac{\pi_{i_1 1,(K)} \pi_{i_2 2,(K)}}{\pi_{i_2 1,(K)} \pi_{i_1 2,(K)}} \qquad (3.22)$$

Odds ratios are then called *conditional odds ratio* when applied to a partial table or *marginal odds ratio* when applied to marginal table. Marginal table is the same table as the one would make if a third variable was omitted. As said before, the analysis of relationships controlled for a third variable are important because they would reveal an extra phenomena such as more rapid changes within one category.

3.8. SUMMARY

A couple of techniques have been presented in this chapter. Linear regression was only mentioned due to its popularity. However, considering socio-psycho acoustic analysis, this model cannot represent reality due to its simple but limited approach. Therefore, group regression model (Groothuis-Oudshoorn et al., 2006) was considered in this section along with Ordinal Regression Model. However, ordinal probit regression model occurred to be involved along with the *cumulative link function* producing exposure-response relationships according to shapes in section (3.5.2).

Finally, an odds ratio technique has been outlined because couple of analysis were conducted on raw categorical variables such as annoyance, noise sensitivity, acceptance of noise, age, and gender. Odds ratio is also found in analysis of logistic regression.

4. DETERMINATION OF NOISE AND VIBRATION EXPOSURES. DETERMINATION OF RESPONSE.

4.1. INTRODUCTION

The purpose of this chapter is to outline methodology regarding calculation and measurement noise and vibration exposure. Vibration was measured by a technical team using dedicated instrumentation. The technical team followed by specific procedures designed for this purpose (See 10 - Appendix C). Noise was calculated according to standard CRN (Department of Transport, 1995) for each site where vibration was measured. CRN and its updated version (Department of Transport, 2007) were inspected before calculation was computed. Although the routine seems to cover most variations that can be anticipated, it was not feasible to include full reality when noise exposure was predicted.

The first section in this chapter provides brief information regarding determination of response followed by explanation of metrics used to express both noise and vibration. In terms of noise, a common noise metric L_{den} was used to express the noise exposure from trains. Although the CRN procedure gives L_{dn}, it seemed to be more adequate to adjust the method from and compute L_{den} instead of L_{dn}. In terms of vibration, two metrics were used to express vibration exposure: $VDV_{b,24h}$ which is defined in BS 6472-1:1992 and RMS W_k defined in European standard ISO 2631:1997.

Further, the chapter provides explanation regarding calculating noise exposure along with discussion on application of L_{den}.

The last section in this chapter explains the uncertainty evaluations during calculation of noise emitted from trains. The reader is referred elsewhere (Craven et al., 2001; Sica et al., 2011) to study this problem in more details.

4.2. DETERMINATION OF RESPONSE

This section presents only a brief review on measurement of annoyance ratings. The responses on annoyance ratings have been gathered by means of social survey questionnaire. The details on development this questionnaire can be find in technical report 2[3] “Measurement of response” (Condie et al., 2011b).

Apart from questions for respondents, the questionnaire also contains information regarding dwelling and surrounding area. The social survey questionnaire have been divided into following sections: vibration questions – this questions meant to gather information regarding feeling or seeing vibrations inside a property or vibration sensitivity; noise questions – similarly to vibration, respondents were asked if they can hear noise inside a property or how sensitive they are about noise; railway vibration – questions about how respondents felt annoyed or disturbed by nearby railway or how annoying were vibration during day, evening or night; railway noise – similarly to railway vibration, participants were asked to rate annoyance due to railway noise; personal and occupancy information – respondents were asked about demographic information (age, gender, ethnicity, employment status, occupation) and about time during week or weekend they were at home.

The questionnaire contains two response scales to measure an individual’s level of annoyance: five point semantic scale and eleven point numeric scale. Details of the choice of annoyance scales can be found in technical report 2 “Measurement of response” (Condie et al., 2011b) and section 3.2.

Both scales were recommended by (DD ISO/TS 15666:2003) for socio-acoustic survey design. It was also recommended by Fields et al. (2001) for socio-vibration survey design. The five-point annoyance scale tend to be designed in a unipolar format, where scale starts from neutral category e.g. "not at all" annoyed, to a negative (e.g. extremely annoyed) position. Fields et al. (2001) analysed the responses of over 12,000 respondents, answering a total of 73 questions about 53 different noise situations. Fields et al. (2001) concluded that the use of five points in a unipolar scale does not result in a heaping effect around the middle point as the middle point does not represent a neutral response (Condie et al., 2011b). After reviewing over 300 surveys exploring noise, the five labels – not at all, slightly, moderately, very, extremely – were identified as being equidistant from one another (Fields et al., 2001). The five point scale was also implemented because it is important that annoyance scales can be comparable to other international research noise or vibration. As noise annoyance research is widely adopting the five-point scale recommended by (DD ISO/TS 15666:2003), it was deemed appropriate and logical to adopt the same scale for vibration annoyance (Condie et al., 2011b).

On the other hand, the purpose of implementing the eleven point numerical scale was that such a scale is easily understood by people from different countries familiar with decimal systems (Fields et al., 2001). Also, eleven points scale were chosen over ten for the same reason as the five point scale to have a sort of midpoint.

4.3. DETERMINATION OF VIBRATION EXPOSURE

4.3.1. Definition of indices expressing vibration exposure

Vibration exposure can be expressed in number of metrics specified in a number of national and international standards with respect to human response. Some of them are listed and considered in analysis for exposure-response relationships in Technical Report 6 (Woodcock, Peris, et al., 2011). In terms of human response, guidance usually specifies an averaging method including time of exposure. Secondly, frequency weighting curves are also provided to specify the sensitivity of humans to the perception of vibration at different frequencies (See Figure 15). Thirdly, weighting curves are applied to acceleration signals so that the human perception to vibration is taken into account. BS 6472-1:2008 suggests the use of VDV ($ms^{-1.75}$) for reporting whole body vibration exposure and ISO 2631-1:1997 suggests the use of RMS acceleration (ms^{-2}) (Woodcock, Peris, et al., 2011).

For continuous signals formula for VDV takes integration instead of summation as follows

$$VDV = \sqrt[4]{\int_{t=0}^{t=T} a_w^4(t)\,dt} \tag{4.1}$$

In the formula (4.1), $a_{\mathrm{w}}(\mathrm{t})$ expresses frequency-weighted acceleration, T a measurement period that a person has received a cumulative measure of the vibration and shock.

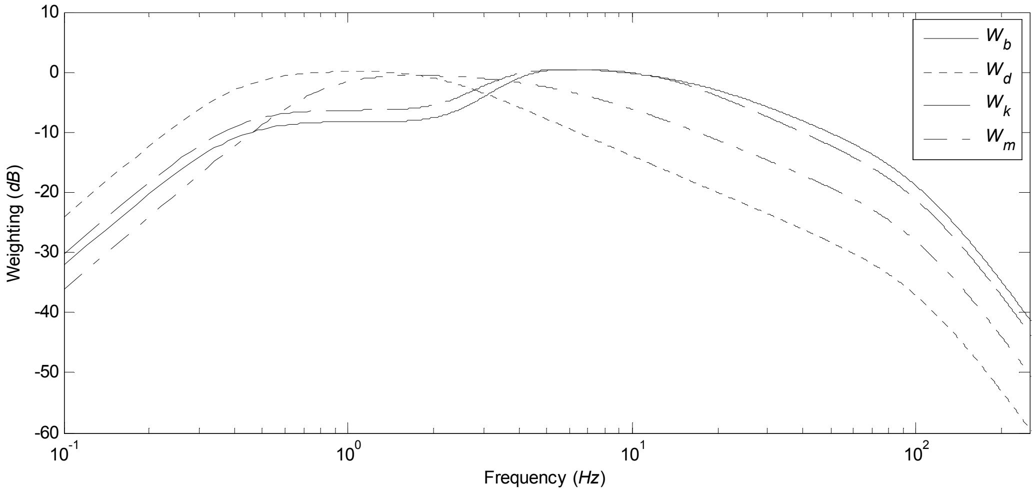

Figure 15. Weighting curves as defined in BS 6472-1:2008, ISO 2631-1:1997, and ISO 2631-2:2003 (Woodcock et al. 2011).

Griffin (1990) and (BS 6472:1992) also provide formulas for the estimated vibration dose value (eVDV)

$$eVDV = 1.4 \times a_{r.m.s.} \times t^{0.25} \tag{4.2}$$

The term $a_{r.m.s.}$ denotes an averaged signal using root-mean squared acceleration. It is however underestimated true vibration dose value (VDV) when the crest factor exceeds a value of six; the higher is the crest factor C_n, the greater will be the error. The crest factor can be computed from the following formula

$$C_n = \frac{|a_{peak}|}{a_{r.m.s.}} \tag{4.3}$$

The term a_{peak} denotes amplitude or maximum possible value in a signal. Weighting curves in Figure 15 are applied to acceleration signal when VDV is calculated. VDV is defined with subscript indicating which of the weighting curves is applied (b or d). They refer to vertical (*b*) and horizontal (*d*) axes (W_b and W_d respectively). The W_b weighting curve indicates maximum sensitivity to vertical acceleration in the frequency range 4Hz to 12.5Hz. The W_d weighting curve demonstrates maximum sensitivity in horizontal acceleration in the frequency range between 1Hz to 2Hz. Additionally to subscript "b" or "d", VDV is also defined with subscript indicating time period that VDV is calculated for over. Subscripts "day" or "night" refer to 16h period during day time or 8h period during night time, respectively. In this Thesis however exposure to vibration is expressed for period of 24h and only vertical component is considered. Therefore, the term velocity dose value is defined as $VDV_{b,24h}$.

ISO 2631-1:1997 recommends the use of the W_k weighting curve for acceleration signals in the vertical direction and the W_d curve for acceleration signals in the horizontal direction. Additional curve W_m is recommended by ISO 2631-2:2003. This curve is applied to acceleration signals in any direction (Woodcock, Peris, et al., 2011). RMS W_k likewise $VDV_{b,24h}$ was calculated for a period of 24h and only vertical component was taken into account. Therefore, RMS is defined as RMS W_k in this thesis (or sometimes denoted as RMS_k).

It has been hypothesised that a number of vibration metrics might be potentially important to express exposure-response relationship based on present data set. However, after analysis, Woodcock, Peris, et al. (2011) has concluded that the choice of vibration metrics is, based on present data set, dictated by ease of calculation, interpretability, current practice, and the measurement capability of the user of the exposure-response relationship. Technical report 1 (Peris et al., 2011) and Technical Report 3 (Sica et al., 2011) presents methodologies of measurements and calculation of vibration metrics respectively.

4.4. VIBRATION EXPOSURE CALCULATED FOR RAILWAY SOURCES

In this Thesis, vibration is considered as a complementary covariate. Measurements and calculation of vibration exposure have been explained elsewhere. Some brief information is provided in two following sections, though. Nevertheless, for more detailed information regarding vibration exposure, the Reader is suggested to study two following reports: Technical report 3 (Sica et al., 2011) to understand the calculation of vibration exposure and Technical report 1 (Peris et al., 2011) to understand the measurement of vibration exposure.

4.4.1. Instrumentation and field measurement procedure

In the report by Peris et al. (2011), it can be read that the accelerometer CMD-5TD was chosen as a most appropriate instrument for measurement vibration inside properties. The choice has been carefully considered based on requirements such as a measurement of the threshold of human perceptibility of vibration as stated in (BS 6841:1987) and

(ISO 2631:1997) (also in (BS 6472:1992), superseded by (BS ISO 6472-1:2008)). Another important requirement for an acquisition of the system was its ease of use.

CMD-5TD is a "force-feedback strong-motion accelerometer" (Peris et al., 2011) used for seismology (also suggested by (ANC Guidelines, 2001)). There are plenty of advantages of using this accelerometer that can be studied in more details elsewhere (Peris et al., 2011; Sica et al., 2011). All in all, the instrument is characterised by following advantages: ease of use, reliability, easy calibration and monitoring the accuracy of measurements, GPS connectivity and synchronization with other similar instruments, a great dynamic range-->140 *dB* for 0.005-0.05 *Hz* and >127 *dB* for 3-30 *Hz*, clip level (output sensitivity) 1g., ability to use outside with batteries provided by manufacturer, water resist.

Figure 16. Guralp CMG-5TD force-feedback strong-motion accelerometer (Peris et al., 2011)

In terms of measurement approach, based on practical experience gained in the field, the interaction between the social survey and the vibration measurement team onsite was conducted as follows:

- The social survey team arrive on site ahead of the vibration team and conduct as many interviews as possible;
- Following an interview, the respondent is asked if they are willing to allow a vibration measurement within the property at a later date and the telephone number of the respondent is taken;
- The vibration team call to book appointments for internal measurements prior to arrival on site (Peris et al., 2011).

The measurement set-up was based on long-term monitoring measurements and synchronized short-term internal measurements. *Control position measurement* was a 24-hour long term monitoring position representative of the site (providing a representative sample of railway traffic) (See Figure 17). It is first placed at the arrival on site. It is selected in a secure location in the near field as the majority of residences of interest were conducted in the near field of the railway. In practice, the control position was generally setup in a resident's garage or garden shed, to avoid contamination from other internal sources (Peris et al., 2011).

Internal Measurements was a short term measurement, which was taken for between 20-30 minutes in order to capture a limited number of train passes (See Figure 17). After the control position is allocated, internal measurements are conducted in properties which agreed for an internal measurement after taking part in the survey. Ideally, internal measurements are taken by mounting the Guralp CMG-5TD units in the room in which the respondent states they can feel the highest magnitude of vibration and following the set-up described in section 3.2.1 (mounting conditions) (Peris et al., 2011).

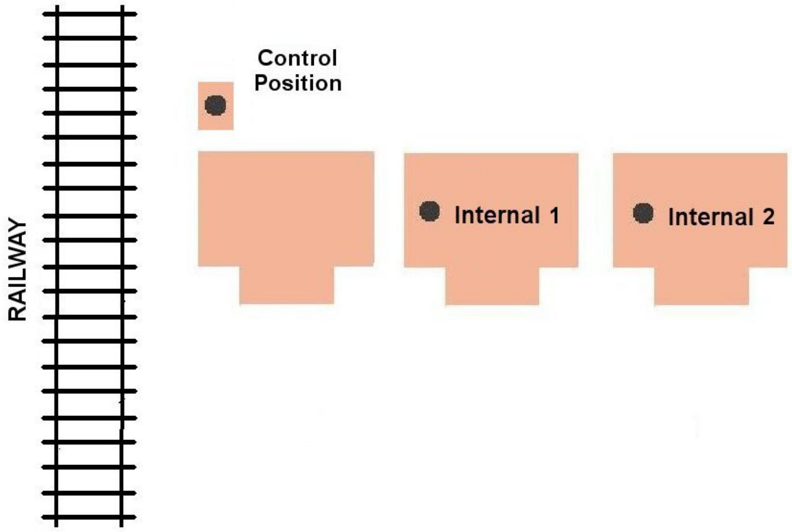

Figure 17. Overview of measurement set up for railway traffic (Peris et al., 2011)

In summary, 522 internal measurements were conducted following interviews at a total of twelve sites. In overall, measurements of railway vibration have been conducted internally in 522 properties, which is 56% of the total number of interviews. However, many respondents didn´t agree to the use of vibration monitoring equipment at their property so in that case considering that internal agreements were not achieved for all respondents, the percentage is slightly higher, achieving a total of 63% of internal measurements over internal agreements (Peris et al., 2011).

4.4.2. Calculation of vibration exposure

Guidance for measuring and evaluating the human response to vibration in residential environment is provided by the British Standard (BS ISO 6472-1:2008, 2008) with the objective to assess the likelihood of adverse comment. Sica et al. (2011) argues that based on British standard (BS ISO 6472-1:2008) human exposure to vibration needed to be recorded as close to the point of entry as possible implying that measurement inside properties should be conducted whenever it was possible. Also, vibration needed to be monitored in sufficient time period. It is argued (Sica et al., 2011) that twenty four hour time period was identified as minimum. In order to conduct all measurements for each resident, a novel approach have been developed. The method has already been outlined in the very previous subsection. Nonetheless, this section also provides some explanation on this matter. The main features of the approach are as follows:

- Long-term monitoring at an external position herein referred as the 'control position'. Where possible, the control position is located at a similar distance from the railway as the affected properties.
- Synchronized short-term snapshot measurement taken in the respondent's dwelling as close the point of entry as possible.
- Calculation of a control-to-internal velocity ratio (frequency dependent) from 1 and 2.
- Calculation of long-term vibration exposure inside the dwelling from 1 and 3 (Sica et al., 2011).

If the respondent is at home or does not agree to an internal measurement, an external measurement should be taken as close to the foundations of the house as possible, if the respondent allows doing so. If the respondent does not agree to any measurement close to the property or is not at home, the external measurement is taken on the street in the front or back of the property (Sica et al., 2011).

Once vibrations have been recorded via accelerometer Guralp CMD-5TD, next step was to extract events from vibration signal. The data for each case study was imported and processed in MATLAB. Events were identified in the Z-direction control position time history data via a process based on a STA/LTA[7] algorithm (Sica et al., 2011) and a control to internal/external velocity ratio for each component is calculated for each event. STA/LTA is an event identification algorithm used to extract train passes on the control position time history. The equation below and Figure 19 illustrate this algorithm in action.

$$STA / LTA = \frac{\frac{1}{STA}\sum_{n=0}^{STA}\left|x_n\right|^2}{\frac{1}{LTA}\sum_{n=0}^{LTA}\left|x_n\right|^2} \qquad (4.4)$$

STA stands for Short Time Average, whereas LTA stands for Long Time Average. The names correspond to the length of frames used to average a part of a signal.

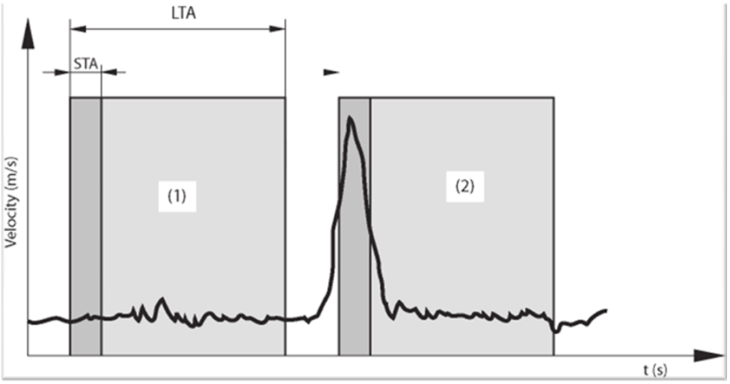

Figure 18. Short time average and long time average windows used by STA/LTA algorithm.

By taking the ratio of STA and LTA, it is possible to (1) filter out very short impulsive events and (2) extract those events which represent train passes. The example of STA and LTA in action is illustrated by Figure 18, whereas the illustrated result from STA/LTA is showed by Figure 19. The algorithm needs to be tuned to an analysed signal; that is, the length of STA and LTA and the threshold have to be carefully chosen. The velocity ratio for each event is linearly averaged to determine an average velocity ratio for the case study under analysis. The average velocity ratio for a case study can then be used to scale the long-term data measured at the control position to predict vibration within a property (Sica et al., 2011).

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[7] Short Term Average/Long Term Average

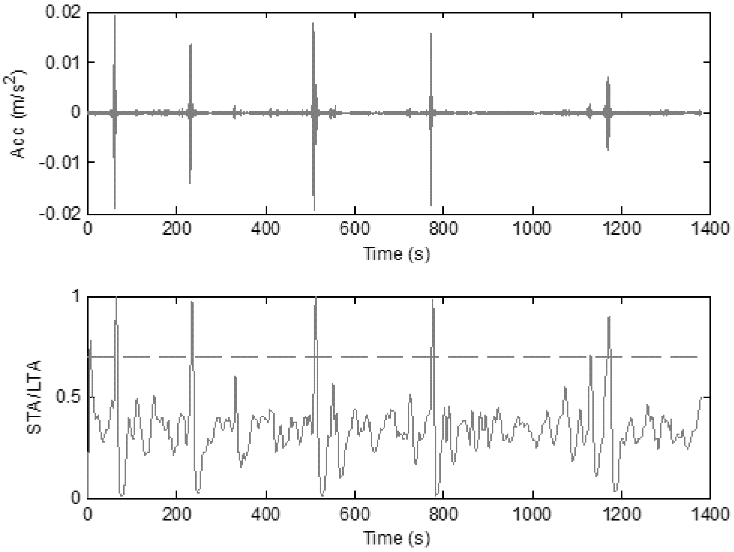

Figure 19. Upper frame illustrates the part of the vibration signal with clear distinct events (long vertical lines) and much lower in amplitude events probably corresponding to impulsive vibrations such as shutting doors etc. By setting proper threshold, STA/LTA can filter out very short impulsive vibration events and keep train passes

The prediction of the exposure from railway vibration was calculated in the following cases: internal measurement, external measurement, and no measurement. In the derivation of the exposure-response relationship only the internal and no measurement cases have been considered. The reason is given by the main aim of the study itself that is oriented in the determination of an exposure response relationship for internal vibration. The high success rate of internal measurement, around 56%, has permitted a good "sampling" of the internal vibration activity in all the measurement sites (Sica et al., 2011). In addition to descriptors for 24-hours vibration exposure, the exposure has also been calculated for the day (7:00 – 19:00), evening (19:00 – 23:00), and night periods (23:00 – 7:00). For the details on computing exposures for internal measurements and no measurements, the reader is referred to "*Technical Report 3*" (Sica et al., 2011).

4.5. DETERMINATION OF NOISE EXPOSURE

4.5.1. Definition for the index expressing noise exposure

To express noise exposure over a 24h time period, a noise descriptor L_{den} has been applied. It is defined as the A-weighted average sound pressure level during daytime (07:00 - 19:00), evening (19:00 - 23:00) and night time (23:00 - 07:00) and imposes a 5 dB penalty during the evening and 10 dB penalty during the night time. L_{den} is calculated from the following formula

$$L_{den} = 10\log_{10}\left(\frac{12\times 10^{L_{day}/10} + 4\times 10^{(L_{evening}+5)/10} + 8\times 10^{(L_{night}+10)/10}}{24}\right) \quad (4.5)$$

L_{den} has been defined in the EC (Directive 2002/49/EC, 2002) and adapted during investigation of exposure - response relationships in similar research studies (Miedema et al., 1998; Miedema et al., 2001; Miedema, 2004). L_{dn} originally calculated from CRN is similarly expressed with difference that evening time is not taken for consideration. Consequently, it is defined in terms of average A-weighted sound pressure level during daytime (07:00 - 23:00) and night time (23:00 - 07:00) and imposes a 10 dB penalty during the night time

$$L_{dn} = 10\log_{10}\left(\frac{16\times 10^{L_{day}/10} + 8\times 10^{(L_{night}+10)/10}}{24}\right) \quad (4.6)$$

4.5.2. Discussion on noise exposure L_{den}

The Table 7 contains four correlation factors calculated on both 5-point semantic and 11-point numeric scales. In both cases, full range of participants and their subset of those reporting percent highly annoyed were taken into account. The Table 7 shows very poor correlation between noise exposure and annoyance scale in both cases when each respondent was considered.

Percentages of highly annoyed (rows 2 and 4) show the increase of correlation between coefficients. Much higher increase can be observed for 5-point semantic scale and very little improvement of correlation can be found for 11-point numeric scale.

Table 7. Correlation factors between noise exposure L_{den} and full range of annoyance scales and their subsets corresponding to %HA

	Noise index	Annoyance scale	Correlation coefficient
1	L_{den}	5-point semantic scale	0.0783*
2	L_{den} (only reported HA)	5-point semantic scale (HA)	0.0457*
3	L_{den}	11-point numeric scale	0.149*
4	L_{den} (only reported HA)	11-point numeric scale (HA)	0.0666*

$N_{full} = 707$; $N_{5\text{-point,HA}} = 81$; $N_{11\text{-point,HA}} = 67$; * $p > 0.05$

Several non-parametric ANOVA tests (Kruskal-Wallis) have been conducted to investigate whether group of respondents reporting to be highly annoyed is significantly different from the group of reporting lower categories. In 5-point semantic scale, this is proportion of people who report categories higher than “moderately” annoyed. In 11-point semantic scale, on the other hand, this is proportion of people reporting categories higher than “8”.

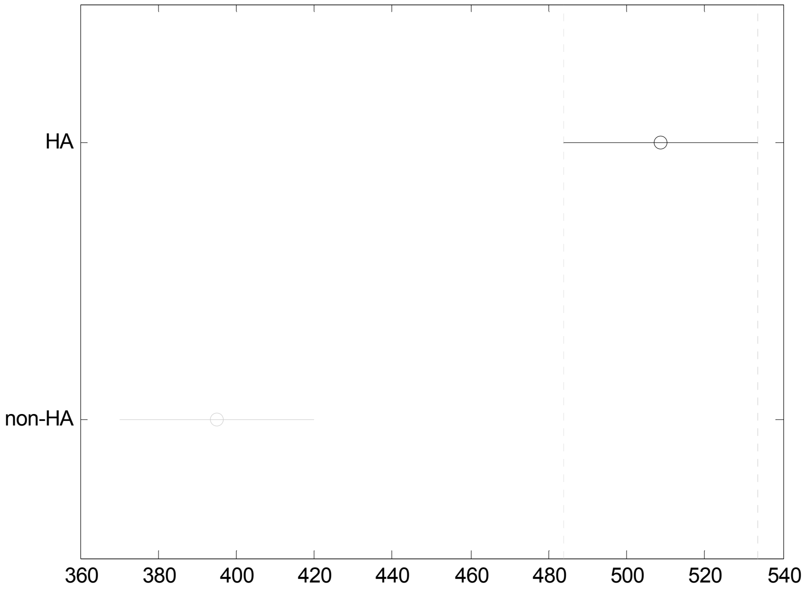

Figure 20. Comparison of two groups %HA and %non-HA reporting annoyance in 5-point semantic scale. The graph indicates significant difference between persons reporting levels of annoyance.

Figure 20 illustrates that two groups are significantly different. The means are out of the range of each confidence interval. The table below presents output from statistic Kruskal-Wallis conducted on aforementioned groups.

Table 8. Output from Kruskal-Wallis test conducted on two groups of respondent highly annoyed and non highly annoyed. Respondents reported annoyance in 5-semantic numeric scale

Source	SS	df	MS	Chi-sq	p > Chi-sq
Groups	1.10E+06	1	1104156	19.88	8.25E-06
Error	4.42E+07	814	54258.7		
Total	4.53E+07	815			

N = 816

The table confirms, similarly to the Figure 20, that there is a significant difference between two groups, when categories are merged into those reporting %HA and %non-HA.

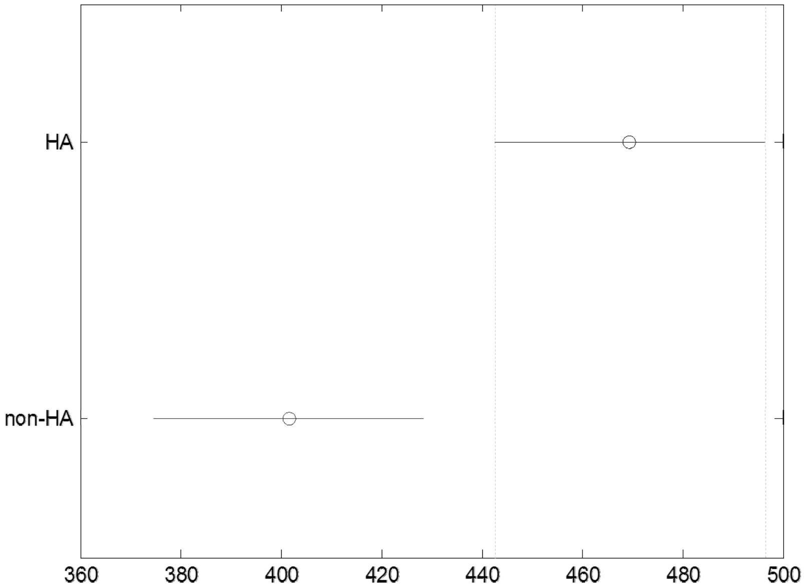

Figure 21. Comparison of two groups %HA and %non-HA reporting annoyance in 11-point numeric scale. The graph indicates significant difference between persons reporting levels of annoyance.

From Figure 21, it is observed that two groups of respondents reporting annoyance in 11-point numeric scale are also significantly different. In this figure, confidence intervals also do not overlap each other indicating that groups reported significantly different annoyance. Table 9 also confirms this in the last cell containing *p* parameter. This value is less than 0.05 which is an expected outcome.

When Figure 20 is compared with Figure 21, it can be observed that CIs in Figure 21 are much closer to each other--*p* value in Table 9 is also close to 0.05 indicating weaker statistical power of the 11-point numeric scale.

Table 9. Output from Kruskal-Wallis test conducted on two groups of respondent highly annoyed and non highly annoyed. Respondents reported annoyance in 11-point numeric scale

Source	**SS**	**df**	**MS**	**Chi-sq**	**p > Chi-sq**
Groups	340702.8	1	340703	6.13	0.0133
Error	44930021	814	55197		
Total	45270724	815			

N = 816

It can be concluded that L_{den} describes noise exposure with required accuracy. As such, further analysis deemed to be conducted with application of this index. Two groups of respondents have turned to be significantly different regardless of annoyance scale. Therefore, it is confirmed that regression models should also give reasonable outcomes in terms of exposure-response relationships.

4.6. MEASUREMENTS OF NOISE EXPOSURE FROM RAILWAY

Analysis are based on prediction from CRN but a couple of measurements were conducted according to standard (BS 7445-2:1991). It specifies the position of a sound level meter in an outdoor measurement such that the instrument is placed at a distance of 1m from the most exposed facade and at a height of 1.5m above ground level. In terms of period, all noise measurements were carried for the same length as vibration measurements, which according to the procedure have been specified to be about 30 min as minimum (See chapter 10 - Appendix C). This period, however, varied due to number of events that has to be recorded. The results obtained from measurements tended to be used for validation of prediction. Despite the conditions specified in CRN (Department of Transport, 1995), for logistical reasons only a selected number of measurements were performed. Additionally, difficulties were encountered in placing the monitoring equipment in a position free from the influence of obstacles within a 50m radius that is specified in CRN.

4.6.1. Results from measurement of noise

Measurements from railway sources played rather additional role and have been conducted in order to investigate a potential possibility to undertake internal measurements. Unfortunately, background noise in most properties was significantly high and prevented from obtaining clear recordings. The other measurements could be utilized as a simple validation or reference to prediction. For this purpose, external measurements have been conducted at the most exposed facade.

Both Figure 22 and Figure 23 illustrate two examples of internal measurements. Figure 22 presents a very noisy event. The value of L_{Aeq} (exceeding 65 dB(A)) at that time suggests possible construction work and the fact a participant was subjected to an extraneous internal noise.

Figure 23 also represents a frequent indoor noise distribution over time. As shown, there were activities at the beginning of a measurement. Their values of $L_{Aeq,1s}$ does not exceed 65 dB(A), which could perhaps suggest a conversation between residents, radio or television in use etc.

On the other hand, external measurements provided much clearer and distinct results. A number of events could be extracted from the overall signal. An example of such a signal can be found in Figure 24.

Figure 25 illustrates a shortened segment of the measurement presented in Figure 24. It should be noted that it is still not possible to identify events occurring outside such as aircraft, trains or road traffic sources. One approach to solve the problem regarding identification of transportation noise is to apply additional equipment to record noise sources and, via revision, identify events manually. More sophisticated approach would involve auto-detecting events or short or long-period monitoring at the site; one microphone at the most practical and convenient location would probably fulfil the purpose. The disadvantage of the latter approach is that the equipment would have been left unguarded and vulnerable to steal for a certain period of time while the technical team was working inside properties.

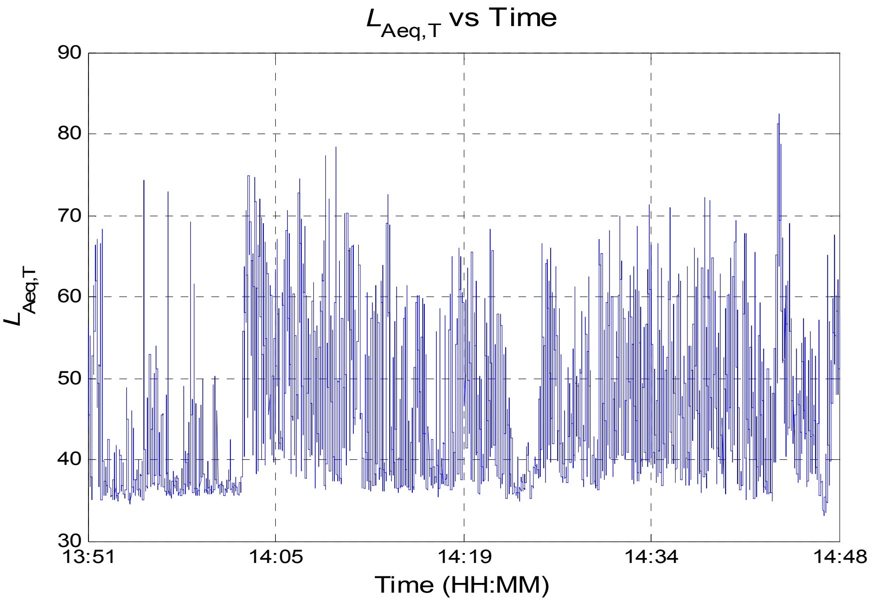

Figure 22. This figure presents an internal noise measurement of a train during the field work. The residence was subjected to an extraneous internal noise. Consequently, as can be seen, it is difficult to distinguish between the indoor extraneous noise source possibly from construction work in the residence and outdoor noise source from a train occurrence.

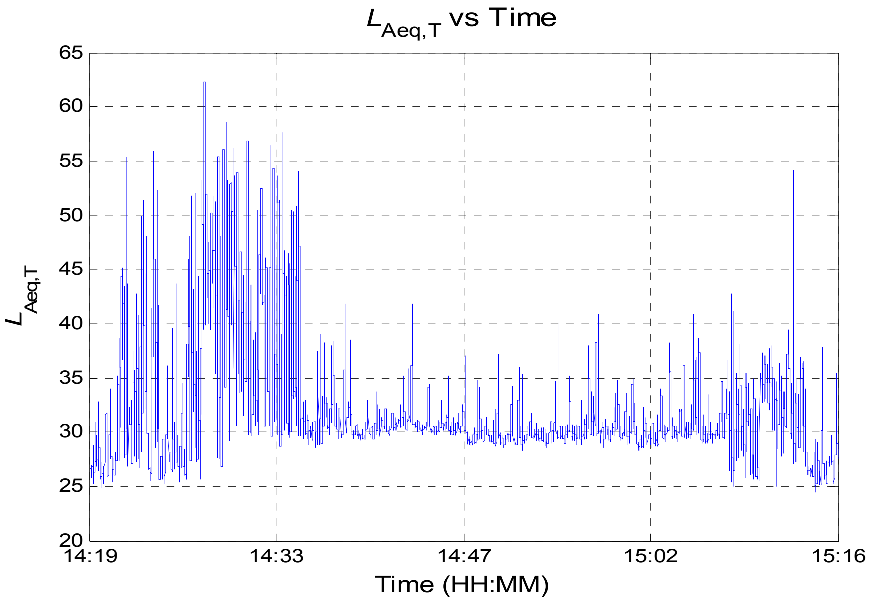

Figure 23. This is part of the whole signal from internal noise measurement. This indicates an initial activity within the residence followed by a period of relative quiet time. A train events were scheduled approximately per every 15 minutes, but the measurements do not indicate associated noise events.

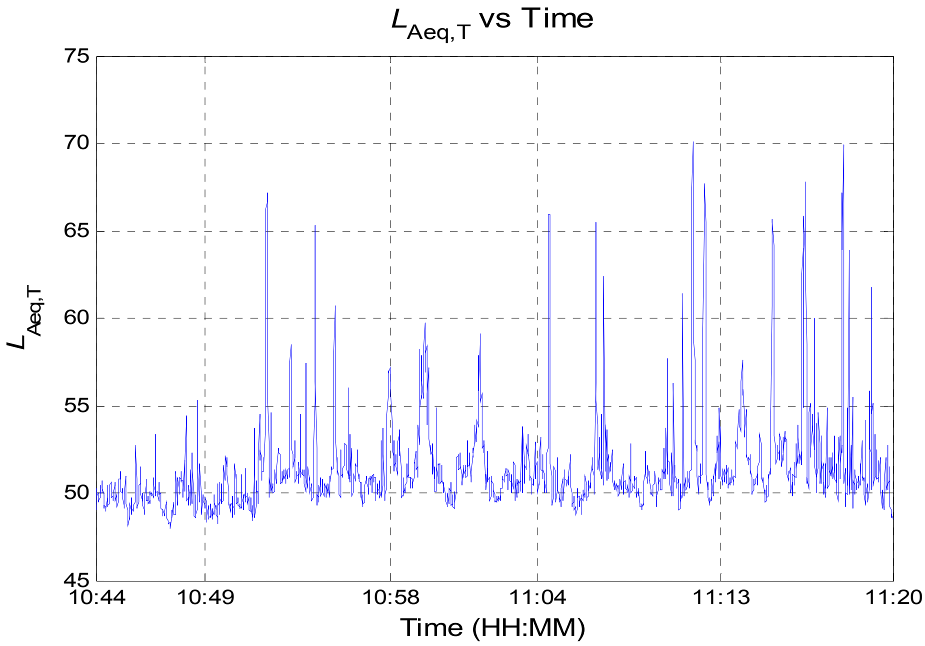

Figure 24. This figure presents external noise measurements. Most events can be identified and extracted from the data.

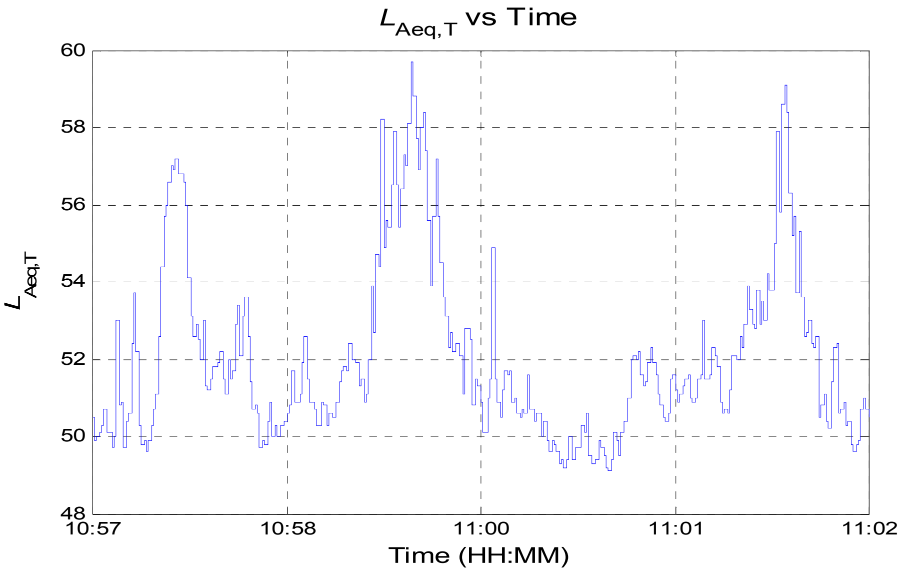

Figure 25. This figure presents a shortened segment of the measurement in Figure 22, indicating 3 separate noise events.

The table below (Table 10) presents sound exposure levels from a measurement. For a comparison purpose, this table also shows predicted values from CRN (Department of Transport, 1995). Only a couple of measurements were conducted during the field work. A microphone was always situated at the most exposed facade, 1.5m above the ground level. The period that noise measurements were conducted for was of the same length as the period that a simultaneous vibration measurement had been conducted. Due to time limitation, a couple of short-term noise measurements have only been obtained. The aim of those measurements was to validate prediction from CRN.

Table 10 shows periods over which measurements took place specifying a number of occurrences during each period. Columns *T* and *T(s)* contain the whole length of time from all events as if it was one continuous event; the two forms have been used: seconds and “HH:MM:SS”.

Discrepancies are an inevitable issue when it comes to prediction and then comparison with real measurements. This is going to be discussed in one of the further sections but it can be clear that prediction appears to overestimate noise exposure from railway traffic for every single property. There are couple of issues encountered during prediction as well as measurements that might probably result with such differences.

Table 10. Comparison of results from measurements and prediction

			Measurement						Prediction	
			Period							
			L_{AE}	Time a measurements started	Time measurements ended	T (s)	T	No occurences	L_{AE}	No occurences
Site A	St. 1	Property a	81.8	10:54:41	11:47:13	153	00:02:33	14	93.4	16
		Property b	82.8	12:07:18	12:37:00	211	00:03:31	6	93.3	16
		Property c	82.9	10:54:59	11:19:39	99	00:01:39	11	90.8	10
		Property d	84.5	12:40:50	13:08:16	296	00:04:56	10	91.4	10
		Property e	85.2	16:07:47	16:45:50	443	00:07:23	14	93.7	18
	St. 2	Property a	80.1	18:55:02	19:19:15	189	00:03:09	8	95.4	28
		Property b	78.9	15:11:52	16:01:43	354	00:05:54	12	93.1	16
Site B	St 3	Property a	81.7	17:25:00	17:57:25	323	00:05:23	11	89.9	4
		Property b	78.3	16:52:16	17:29:08	189	00:03:09	6	86.2	4
	St. 4	Property a	84.2	19:07:09	19:33:08	519	00:08:39	11	83.2	3

In terms of measurements, sound sources were shielded by obstacles located on the path between source-receiver including sheds, high fences, lower level of noise sources. These objects could significantly reduce the noise level by the value of 10 dB(A) or more. Sections 4.7.1 until 4.7.5 present and discuss procedures and results from prediction.

4.6.2. Observation

An important observation from the preceding section is that for environmental noise, the definite discrepancy exists between results obtained from internal and external measurements. The main reason of this section is to justify whether internal measurements needed to take place.

Figure 23 shows indoor activities such as conversation, radio, television etc. In terms of noise level arising from internal and external sources, differences indicate that external noise sources can be effectively masked by internal sources. At this site, train passed by a reception point regularly every 15 minutes. The figure presents some outdoor activities. However, it is worth noting that in the part of the measurement corresponding to a period of low level of noise, external sources hardly exceeds 45 dB(A) whilst an average of level of an internal source is found to be about 55 dB(A). Results from measurement of external events, having such a low sound level, were found difficult to deal with. Therefore, it was rather infeasible to determine an internal exposure from internal measurements. Hence, it is thought that the best approach is to assume that external exposures might decently correlate with internal exposures. A number of documents regarding noise exposure, response and annoyance relationships rely on external exposure calculation with the same assumption (Fields et al., 1982b; Miedema et al., 1998; Miedema et al., 2001; Schultz, 1978). There is only slight evidence of a correlation between an internal and an external exposure but a few papers assume that the correlation exists although not having sufficient data (Graham et al., 2009; Shield et al., 2004).

4.7. CALCULATION OF NOISE EXPOSURE FROM RAILWAY

Noise exposure from railway traffic was predicted from CRN. In terms of period, all noise measurements were carried for the same length vibration measurements, which according to the procedure have been specified to be 30 min as minimum. This period, however, varied due to number events recorded. Although two approaches were considered towards validating the results from the prediction, a more sophisticated method will be required. Such a validation would require more measurements to compare from different sites. Owing to time constraints, the acquisition of the required number of measurements is not currently feasible.

4.7.1. Noise estimation from Calculation of Railway Noise

CRN (Department of Transport, 1995) defines a routine covering all details influencing the final noise emission from railway vehicles passing by a point of reception. Additionally, CRN covers site topography, ground reflection, number of vehicles per train, number of trains per 24 h, air absorption (although this is primarily a high frequency effect), distance correction, barrier attenuation, reflections from facades as well as the reflective contributions of buildings surrounding the point of reception. The most significant and accurate approach, however, requires a great deal of detailed information regarding sites. Therefore, the prediction is based on a number of assumptions. The number of trains was estimated based on event extraction from signals from control positions monitoring vibration for 24 h in the vicinity of rail lines. The details upon this topic can be found in Technical Report No 3 "*Calculation of Vibration Exposure*" (Sica et al., 2011).

4.7.2. Assumptions Imposed

The first of the assumptions refers to the train speed. Each train, and hence its constituent vehicles, has a maximum speed dependent upon the type of the train, e.g. Class 390 (*Pendolino*) are probably the fastest trains that can reach a high speed similar to 200 km/h. On the other hand, older trains such as Class 170 (*Turbostar*) are much slower whose speed would probably not exceed 160 km/h.

The second assumption covers a number of vehicles that trains are comprised of. More vehicles greatly increase sound exposure level. Class 390 uses trains composed by 9 vehicles. This is an additional issue as some of the vehicles work as a power feed. Therefore, vehicles can be Driving Motor, Intermediate Motor, or Intermediate Trailer etc. Trains such as *Pendolino* (Class 390) are called an electric multiple unit (EMU), similarly to diesel multiple units (DMU). Despite the variation in terms of a vehicle function, a L_{AE} correction from a single vehicle is found to be either 7.6 or 6.0 dB(A). There are number of configuration of trains which can be found in CRN. In terms of non-multiple units, a vehicle can be either a locomotive or a coach/wagon. On local railway routes, a number of two vehicles per train was found more common. It was non-feasible to apply separate number of vehicles to each train. Therefore, an average number of vehicles was assumed to be 5.

Another assumption refers to noise emissions from a single vehicle. The noise emission is assumed to be constant for all constituent train vehicles, and so a correction of 7.0 dB(A) per vehicle was assumed.

The distance between rails and the point of response was estimated from Google Maps. A different number of tracks can be found in different rail lines. CRN (paragraph 19) requires the source to be a near-side rail head. However, at almost each site, the railways traffic operated in two directions. The distance of sources was different depending on the train directions. Thus, the distance was assumed to be taken from the average between the nearest rails for all trains operating in both directions.

Where it was possible, the effect of cutting-off of a source was applied and prediction of noise exposure was significantly reduced. However, due to difficulties of recognizing the ground topography, the appropriate corrections are included in evaluation of uncertainty (See section 4.8).

Reflections from opposite buildings were neglected in prediction.

4.7.3. Calculation

Calculations of noise exposure were conducted for passenger and freight trains. The number of trains was obtained from estimating times of all events from all control positions measuring vibration for 24h. If there were more than one control position, monitoring the same rail line (see Figure 26), an average number of train occurrences from all the control positions monitoring the same line was calculated and applied separately during a day-time, evening-time and night-time periods. The average number had to be taken due to slight differences in detecting a number of events from more than 1 control position.

Table 11 presents the number of control positions per site. The number of two control positions was common, although more instruments had to be set up, occasionally. The number of control positions came from a limit that one instrument can measure vibration within a radius of 80 m. If a length of a site was greater than this limit, more instruments were set up.

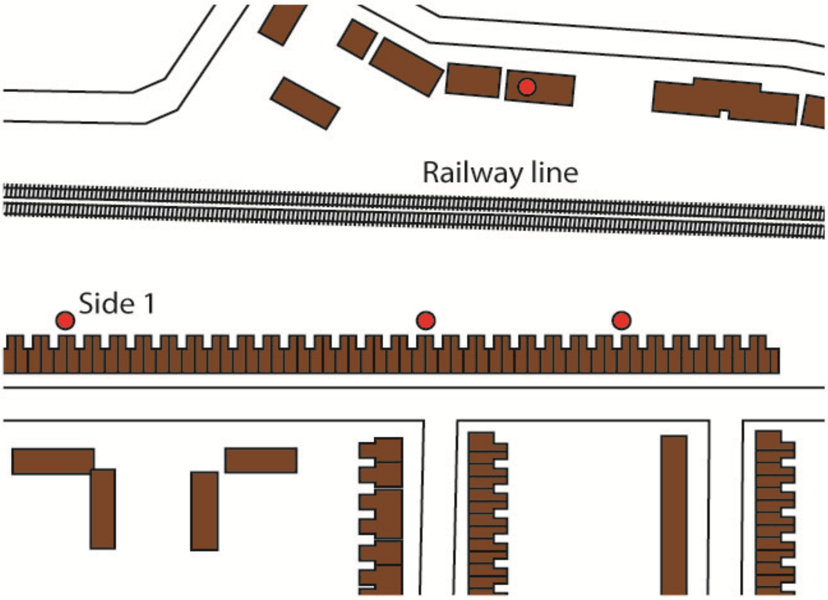

Figure 26. This figure shows an example of 2 sites located close to each other. The same railway was situated in such location that all residents from different sites were exposed to noise and vibration from the same trains. The monitoring of vibration by all control positions took 24h, however, the measurements were started at different time.

The number of passenger and freight trains estimated for one of the many railway lines is presented in Table 12. The algorithm used for extracting particular events is explained in Technical Report 3(3) "*Calculation of Vibration Exposure*" (Sica et al., 2011). Numbers of freight and passenger trains for the other sites were estimated in the same way.

Table 11. Number of Control Positions for different sites

Site	Number of Control Positions
Site A	2
Site B	2
Site C	2
Site D	2
Site E	1
Site F	4

Table 12. Example of estimating the number of passenger and freight trains on a site

	Passenger	**Freight**
Day (07.00 - 19.00)	117	1
Evening (19.00 - 23.00)	40	1
Night (23.00 - 07.00)	23	2

The routine for calculating L_{AE} and therefore L_{den} for every respondent is following:

- A number of passenger trains and a number of freight trains during daytime, evening and night-time was estimated from control positions
- L_{AE} corrections are assumed to be 7 dB(A) for passenger train vehicles, 14.8 dB(A) for a freight train diesel locomotive and 7.5 dB(A) for a laden freight train vehicle (wagon)
- Speeds of passenger and freight trains were assumed based on information provided by Network Rail
- The position of noise source for passenger trains was set to 0.25m above the ground (the point where noise emission high speeds) for all vehicles except diesel locomotives operating under full power, which required the effective source position of four meters above the ground level
- The distance between point of source and reception was calculated from aerial data; including, whenever it was possible, path length differences caused by cuttings off
- Distances were estimated from Google Maps (Google Inc., 2011) and applied to calculations as an average between both railway lines

- Corrections due to the number of vehicles were applied separately for daytime, evening time and night-time, and L_{AE} was calculated
- three components comprises of 24h noise index L_{den}: L_{day}, $L_{evening}$ and L_{night} were obtained, followed by calculation of L_{den}

4.7.4. Results

This section presents results from calculation of 24h exposure to noise from railway traffic according to EU Directive (Directive 2002/49/EC, 2002).

Table 13 shows results of prediction obtained from calculation based on CRN. Although such sites were subjected to a high frequency of freight traffic during the measurement periods, this would not necessarily be the case at other times. This is because freight trains do not travel regularly according to any scheduled timetable. The quietest observed site can be explainable by the fact that only a small number of trains are scheduled to pass the reception point. Additionally, freight trains were not always encountered during measurements but some of them were extracted from the control position signals monitoring vibration for 24h. It is noteworthy that the analysis is based on only 24h windows of measurements. In this time, freight train pass-bys might or might not occur. Additionally, not all rail lines / tracks are dedicated to be used by freight trains, that is also the reason why a couple of sites seem to be noisier with regard to the period of twenty four hours.

Table 13. shows values of calculated external noise exposures from CRN of all sites presented in three columns; an average, a maximum value and a minimum value. The results in the table consist of a combination of passenger and freight trains

	No of respondents	Av. Lden	Min Lden	Max. Lden
Site A	115	57.9	40.4	61.2
Site B	30	58.0	49.7	61.5
Site C	9	53.8	51.3	56.0
Site E	64	67.2	58.6	73.9
Site F	61	59.6	54.4	63.1
Site H	87	62.2	56.9	68.0
Site I	155	63.2	57.0	68.6
Site J	235	60.2	53.1	66.9
Site K	45	61.0	49.6	70.4
Site L	43	62.9	57.4	67.4

4.7.5. Justification and discussion on the methodology of prediction

The choice of prediction was dictated rather by constraints found during the work for the Defra funded project. Due to vast number of vibration measurements conducted during the field work, prediction may have only been the reasonable choice to obtain a correct set of noise exposures for each property where vibration exposure had already been conducted for. Technical issues made it infeasible to conduct measurements at each site. If accuracy from prediction is somehow questioned, it is definitely not a methodology issue. Calculation of Railway Noise (Department of Transport, 1995) was and probably still is one of the best routine to obtain a reasonable prediction from railway traffic. In this project, the issue was the ability to recognise a site from maps. It is though concluded that, discrepancies are significant but the results from analysis can still provide reasonable outcomes.

Table 10 and Table 14 present prediction for sound exposure levels compared with measurements of the same noise index L_{AE} and prediction compared to noise map from Defra, respectively. If one considers prediction from CRN and prediction from noise map, one can find that numbers are of the similar range.

Table 14. presents a comparison between L_{day} determined from Calculation of Railway Noise and Noise Map values obtained from Defra.

Address	**L_{day}/dB(A)[9]** **Predicted from CRN**	**L_{day} /dB(A)[9]** **Read from Noise Map**
Site A, Street 1	52.3	58.6
Site A, Street 2	58.6	58.1
Site F, Street 1	58.3	55.5
Site F, Street 2	57.9	54.7
Site F, Street 3	58.9	50.6

By examining Table 10 (See section 4.6.1, p. 59), one can find significantly high discrepancies between measurements and prediction. The first problem appearing as an immediate issue is that prediction is always higher for each property; meaning prediction seems to highly overestimate noise exposure. One of the reasons is probably the fact that most objects influencing on final noise level could not be included in prediction. Secondly, the difference may also be caused by a number of events extracted from control positions and a number of events obtained from noise measurements.

Table 10 shows different number of occurrences which can reach even 20. In dB this is equal to 13 dB(A) ($10*\log_{10}(20)$).

Uncertainties regarding prediction of noise exposure have been calculated and presented in Table 17. The main uncertainties were due to differences in the number of vehicles, which varies from train to train. Trains operating between local stations typically comprise of two or a maximum of three vehicles. Conversely, fast long distance trains typically comprise of five or nine vehicles. Due to aforementioned issues regarding prediction, uncertainties became quite significant in number. The same outcome can be observed studying Table 10 on page 63. Most predicted sound exposure levels became much higher from their measured equivalence. Considering all unaccounted issues regarding computation of prediction, uncertainties became equal to +/- 10 dB(A) which is the worst possible error after considering each possible issue.

4.8. UNCERTAINTY EVALUATION ASSOCIATED WITH CALCULATION OF NOISE EXPOSURE

4.8.1. Introduction

Craven et al. (2001) describe the methodology of calculating the uncertainties outlined in the following section, of which there are 3 pertinent categories;

- Uncertainties due to external measurements of train event occurrences
- Uncertainties due to internal measurements of train event occurrences
- Uncertainties due to calculation of exposure to noise based on Calculation of Railway Noise

More detailed explanation of uncertainties was included in Technical Report 3 "*Calculation of Vibration Exposure*" (Sica et al., 2011).

4.8.2. Uncertainties due to external measurements of train events occurrence

Relatively few uncertainties are associated with noise measurement for railway traffic noise (See Table 15). The primary issue resulting in the highest level of uncertainty was ground between the source and receiver which was usually found to be composed of a combination of grass and concrete, each of which demonstrate different absorptive and reflective properties. Results from measurements were also influenced by a number of obstacles which varied in terms of size and composition material, resulting in variations of sound energy reflection. Due to regular calibration and sensitivity checks of the measurement equipment, only a small uncertainty value is associated with the receiver signal chain.

4.8.3. Uncertainties due to internal measurements of train events occurrence

Uncertainties associated with internal exposure calculation are presented in the Table 16. The most difficult issue found during the limited number of indoor measurements was the very low internal level of external noise sources (those of main interest). With such a low level of sound pressure, it was not considered feasible to obtain data upon which analysis could be performed with sufficient accuracy.

Table 15. Uncertainty budget evaluation for external noise exposure from railway sources.

Uncertainties	Notes	Lower / Upper limit	Distribution	Standardised. Uncert.
Transmission path				
Barriers	At most sites, small obstacles were present	± 0.5 dB(A)	Rect.	0.289
Ground influence	Attenuation due to soft ground and height of source	± 1.5 dB(A)	Rect.	0.750
Receiver				
Sound Level Meter		±0.5 dB(A)	Rect.	0.577
Position of SLM	CRN requirements include position of SLM such that height of the reception point should be located in the range 1.2m above the ground (minimum) to 3.5m above the railhead (maximum); measurements were taken at a height of 1.5m	0.1 dB(A)	Rect.	0.058
COMBINED Uncertainty (root sum of squares)				0.99 dB(A)
EXPANDED uncertainty (95% confidence [k = 2])				1.98 dB(A)

4.8.4. Uncertainties from calculation of railway noise

A greater number of uncertainties are expected from calculation of an exposure to noise from railway traffic using predictive methods. Uncertainties mainly arise from assumptions made regarding the number of vehicles that trains are comprised of, the number of trains during the day, evening and night periods (although this was evaluated from control positions monitoring vibration from trains for 24h), the distance between the source and receiver estimated using Google Maps (Department of Transport, 1995), the ground correction which differs from site to site and the speed of trains travelling through residential areas, where differences in speed are dependent upon on grade, area etc. It is worth noting that ground correction was included in calculation of overall exposure to noise, although difficulties arose due to uncertainties regarding ground composition – whether it was only covered by grass, comprised of concrete slabs or a mix of both. CRN covers this problem although the level of accuracy is dependent upon the routine implemented therein.

Table 16. Uncertainty budget evaluation for internal noise exposure from railway sources

Uncertainties	Notes	Lower / Upper limit	Distribution	Std. Uncert. (dBA)
Source				
Spectral content	Each trains are mostly a low and middle frequency noise sources	± 1.0 dB(A)	Rect.	0.577
Transmission path				
Ground correction	Sites vary in terms of ground reflection which requires inclusion in CRN	± 0.400	Rect.	0.231
Barriers	The area of trees and fencing between source and receiver	± 0.5 dB(A)	Rect.	0.083
Attenuation due to walls in a property	Additional attenuation of the measurement introduces extra uncertainty due to issues such as single or double glanced windows, windows are open or closed	± 10.0	Rect.	5.77
Distance		0.100	Rect.	0.058
Topography	Different whether an effect of noise reduction from cutting-offs or embankment takes place	1.000	Rect.	0.577
Obstacles	Sheds, fences, trees etc.	0.5	Rect.	0.289
Indoor Receiver Position				
Mic. orientation	Some standards suggest orienting mic. towards source as opposed to manufacturer recommendations (vertically)	± 0.5 dB(A)	Rect.	0.289
Dynamic range set	Insufficient dynamic range for spectral content measurements	± 1.5 dB(A)	Rect.	0.750
Background noise	Significant level of background noise observed during measurements	± 1.5 dB(A)	Rect.	0.750
Str., grd-borne sound	Negative influence of standing waves, structure and ground-borne sound	± 1.5 dB(A)	Rect.	0.750
COMBINED Uncertainty (root sum of squares)				**10.1 dB(A)**
EXPANDED uncertainty (95% confidence [k = 2])				**20.2 dB(A)**

The main uncertainties were due to differences in the number of vehicles, which varies from train to train. Trains operating between local stations typically comprise of two or a maximum of three vehicles. Conversely, fast long distance trains typically comprise of five or nine vehicles. Table 17 presents uncertainties associated with calculation from CRN.

Table 17. presents uncertainties associated with calculation for railway sources based on Calculation of Railway

Source of Uncertainty	**Notes**	**Lower / Upper limit**	**Distri bution**	**Standardised Uncert.**
Source				
Noise emission	Vehicles vary in terms of noise emission – locomotives, EMU, DMU etc.	± 0.800	Rect.	0.462
No. of vehicles	Trains are comprised of a different number of vehicles varying between 3 - 9	± 3.400	Rect.	1.963
Velocity	Train speeds are applied considering train speed limits for different sites; each train (Class 390 and Class 170) can be permitted to a different speed limit within an area whose variation may be found of max. by 25 mph (40 kmph)	± 2.000	Rect.	1.155
Occurrences	A different number of occurrences from measurement and prediction was found	± 0.500	Rect.	0.289
Transmission path				
Ground correction	Sites vary in terms of ground reflection which requires inclusion in CRN	± 0.400	Rect.	0.231
Barriers	The area of trees and fencing between source and receiver	± 0.5	Rect.	0.083
Distance		± 0.100	Rect.	0.058
Topography	Different whether an effect of noise reduction from cutting-offs or embankment takes place	± 1.000	Rect.	0.577
Obstacles	Sheds, fences, trees etc.	± 0.5	Rect.	0.289
Receiver				
Microphone	Standard uncertainty evaluated for SLM	± 0.5	Rect.	0.289
COMBINED Uncertainty (root sum of squares)				**5.4 dB(A)**
EXPANDED uncertainty (95% confidence [k = 2])				**10.8 dB(A)**

4.9. UNCERTAINTY EVALUATION ASSOCIATED WITH VIBRATION EXPOSURE

The evaluation of uncertainty budges regarding calculation of vibration exposure from railway was provided in the Technical report 3 (Sica et al., 2011). Briefly, important aspects of theory were presented in this document followed by calculation. In general, in terms of results, three categories can be considered: internal measurements, external measurements, and no measurements. In document by Sica et al. (2011), the results are provided in two categories as follows:

Internal Measurement	±2.2 dB
No Measurement	±6.2 dB

The term *Internal Measurement* corresponds to measurements which took place inside properties. The term *No Measurement* means that vibration exposure for a particular property had to be obtained from prediction. Such situations took place if nobody could give permission for vibration measurements inside or outside a property. Consequently, vibrations were predicted based on wealth data set from the other similar buildings. However, due to prediction of exposure, the uncertainty had to be risen.

4.10. SUMMARY

This chapter provided an outlined explanation on determination of response followed by outline on metrics applied to describe vibration exposure. Finally, a detailed explanation was provided with regards to noise exposure.

The noise index L_{den} is found to be questioned in socio-acoustics surveys, yet it still remains a widely accepted common measure of noise exposure. It was found that L_{den} does not fully reflect the phenomenon of exposure-response relationship to transportation noise because the percentage of variance accounted for this relationship is found to be low. There is a number of other non-acoustical factors that influence on annoyance caused by railway and these factors are not implemented or accounted for exposure-response relationship to noise when noise exposure is expressed by L_{den}. Nevertheless, it can be found that L_{den} is suggested by (Directive 2002/49/EC).

The noise was calculated from CRN (Department of Transport, 1995) including the update of this document (Department of Transport, 2007). For expression of noise exposure, this document suggests to compute noise index L_{dn}. Therefore, the methodology was adjusted to fulfil the recommendations and express noise exposure as L_{den}.

In terms of vibration exposure, two metrics are used: $VDV_{b,24h}$ and RMS W_k. Based on present data set, these two metrics become important after comparing them with other vibration metrics which might be potentially important to express exposure-response relationship with respect to vibration (Woodcock, Peris, et al., 2011).

Finally, this chapter provided uncertainty evaluations due to calculation from CRN (Department of Transport, 1995) because values predicted from this document cannot be certain. CRN provided the routine that covered most common situations encountered at sites but there are still individual issues that cannot be anticipated. The change of speed of trains is such an example. It is not feasible to predict each instant change of the train speed. In the worst case, speeds were assumed to be maximal at a particular parts of a rail line. Sometimes trains were operating at their full speed (200 km/h) or only at 30 mph. These nuisances were included in uncertainty evaluations.

On the top of issues listed in this section, it is thought that conclusion from this section can still be valuable and of high importance, because vast number of studies relies on averaged sound level, L_{den}. Plenty of studies have already investigated dose-effect relationships using noise indices such as L_{dn} and L_{den}.

5. EXPOSURE-RESPONSE RELATIONSHIP AND EFFECT OF FACTORS ON ANNOYANCE.

5.1. INTRODUCTION

The objective of this chapter is to provide results from analyses of noise, vibration, and combination of these effects. The chapter starts with presenting exposure-response relationship to noise and discussing three threshold curves indicating percent annoyed given noise exposure. Noise has been expressed by L_{den} which is defined as a 24h noise exposure index including penalties of 5 dB(A) and 10 dB(A) added to the evening and night time periods represented by components $L_{evening}$ and L_{night}, respectively (See section 4.5).

Noise exposure is further analysed and discussed with regard to sleep disturbance. The different proportions of annoyed can be observed when this effect is considered. Because the sleep disturbance has been found to be an important influential factor, this effect has also been investigated with relationship to noise sensitivity and noise acceptance while those effects have been controlled for noise exposure.

Reviewed literature provides evidence on non-acoustical factors (demographic and attitudinal) that have also effects on annoyance while respondents are affected by noise from transportation modes. Therefore, a number of factors have been investigated but conclusions have been provided for noise sensitivity, age, and gender.

The following section presents a number of graphs illustrating exposure-response relationship to vibration expressed via two indices such as $VDV_{b,24h}$ and RMS W_k. The graphs illustrate percentage of highly annoyed along with little and moderately annoyed. Vibration is also analysed with respect to sleep disturbance but this effect is discussed elsewhere in more details.

The chapter ends with discussion on combined effects from noise and vibration. However, a point has to be made about the fact that vibration was included as a complementary effect and therefore analyses are limited to vibration exposures calculated from 24h weighted acceleration time period. Nevertheless, the section provides evidence that annoyance may increase when both effects occur. To provide a full demonstration on the latter fact, a set of two- and three-dimensional graphs have been provided in the section preceding Summary.

5.2. EXPOSURE-RESPONSE RELATIONSHIP TO NOISE

In section, seven graphs present results from analysis of exposure-response relationship to predicted noise from CRN. Noise exposure has been calculated for 931 cases. It is expressed by L_{den} which an index covering 24-hours time period. Response, on the other hand, was measured via a social survey questionnaire conducted during face to face interviews. The curves in following figures illustrate thresholds of proportion of participants reporting little, moderate, and high annoyance. Although definition of these thresholds is provided elsewhere (See section 3.2), it is noteworthy that the curves indicate maximal proportion of people expected to report certain annoyance degree. Additionally, each graph provides 95% Confidence Intervals indicating fluctuations around mean. A few graphs provide scatter plots illustrating the cause of confidence intervals. The last graph provides a distribution of changes of a number of people who reporting reported hearing noise from railway.

5.2.1. Relationship between noise exposure and annoyance

The annoyance effect from noise induced by railway events was measured in 5-point semantic scale and 11-point numeric scale (See section 3.2). To assess annoyance cased by railway traffic noise, residents were asked the following question the (Condie et al., 2011a, 2011b):

> *Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by hearing noise caused by railway? Would you say not at all, slightly, moderately, very or extremely?"*

Figure 27 illustrates the exposure-response relationship from predicted railway traffic noise. Three curves represent degree of annoyance as follows: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). The curves have been drawn via ordinal probit model. Its description can be found elsewhere (See section 3.2) along with definition of each annoyance degree.

Figure 27 can be read in following way: at L_{den} = 65 dB(A), maximal 45% of participants report little annoyance (%LA); at the same noise level, 16% of participants report high annoyance (%HA). The number of LA% is expected higher than %HA because %HA is included in %LA. Figure 27 clearly shows that the higher the noise exposure, the higher proportion of people reporting any annoyance degree.

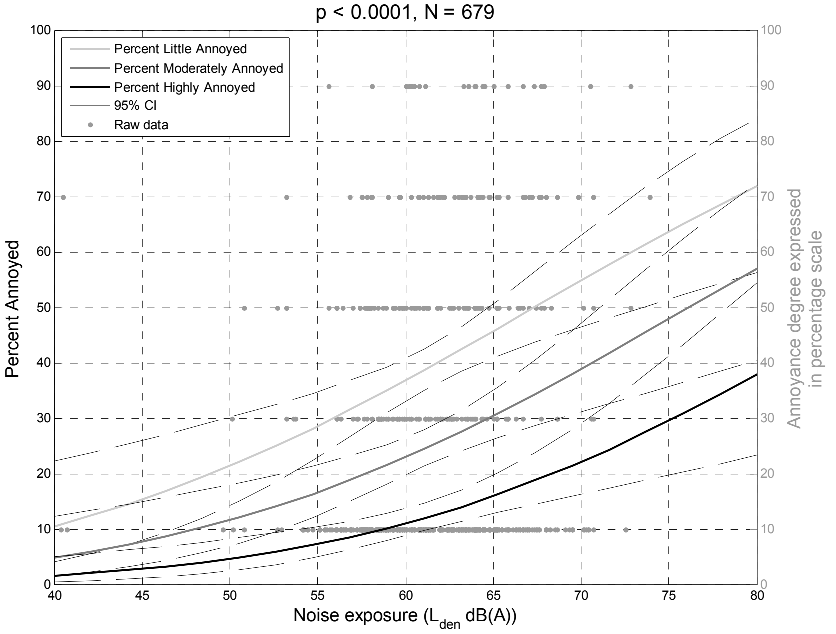

Figure 27. Percent little, moderately, and highly annoyed vs. noise exposure from railway with 95 % of confidence intervals. Annoyance measured via 5-point semantic scale.

The 95% Confidence Intervals illustrate expected variations around each mean given a level of noise exposure. Therefore, instead of expecting a fixed number of 45% given 65 dB(A) of %LA, one may expect fluctuations between 42% and 51% occurred ninety five times out of hundred.

Similar to Figure 27, Figure 28 illustrates annoyance curves long with scatter plot. The purpose of this graph is to provide the explanation of one the causes of 95% confidence intervals--the missing middle curve has been excluded because (1) scatter is already difficult to read and (2) %HA are consider most important group of people.

Unfortunately, the scatter plot could not be obtained from the ordinal regression model. Therefore, data points were calculated manually. Noise exposure has been split into categories of 2 dB(A) range. Each category groups a number of participants falling into each noise exposure category. From this number of people, a subset of those who report greater annoyance degree was extracted. Finally, the proportion between a number of people reporting higher degree of annoyance within each noise category and number of people representing the whole subset of this category was calculated. This proportion is represented by each point of the scatter.

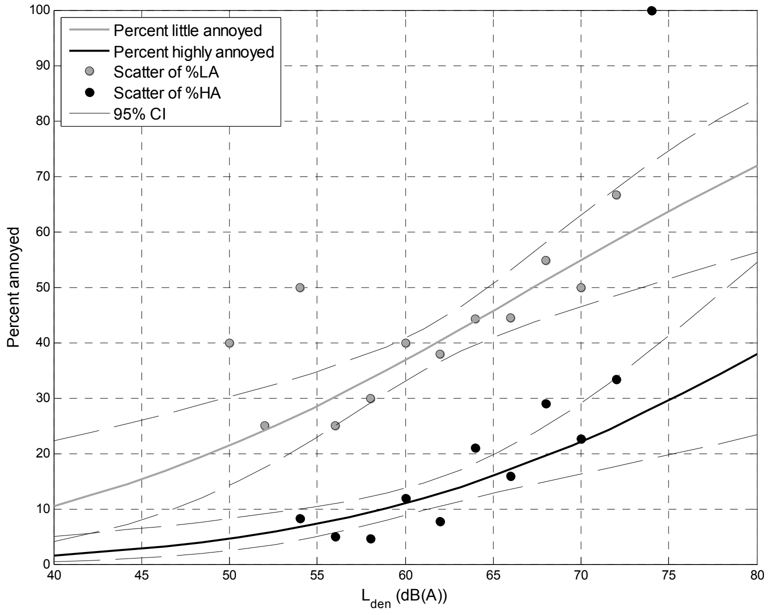

Figure 28. Percent little and highly annoyed vs. noise exposure from railway with scatter plot. Annoyance measured via 5-point semantic scale.

Two factors influence on the width of the confidence interval. On one hand, the width is the result of an estimation of a regression model when a covariate matrix is known (See section 3.5). On the other hand, the higher spread of data points, the wider is the confidence interval while a number of points are the same.

The influence of these two factors can be seen in both Figure 27 and Figure 28. Due to the mean at ~ 61 dB(A), the confidence intervals are the narrowest. From Figure 28, it can be observed that %LA are slightly more scattered especially at lower noise exposure. One of the reason, also supported by Schultz (1978), is that people could not hear noise from railway. The outdoor noise exposure may be easily masked by indoor activity (See Figure 22 and Figure 23 illustrating indoor noise level emitted in two properties).

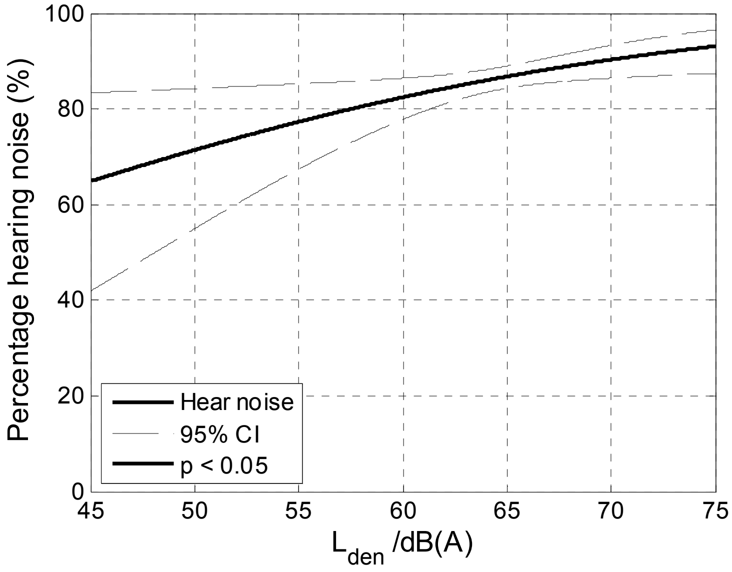

Figure 29. Proportion of people who could hear noise from passing trains.

It has to be noted that Figure 29 is plotted from assessment whether people could hear noise. However, it is not known whether people could or could not hear noise because windows were opened or closed.

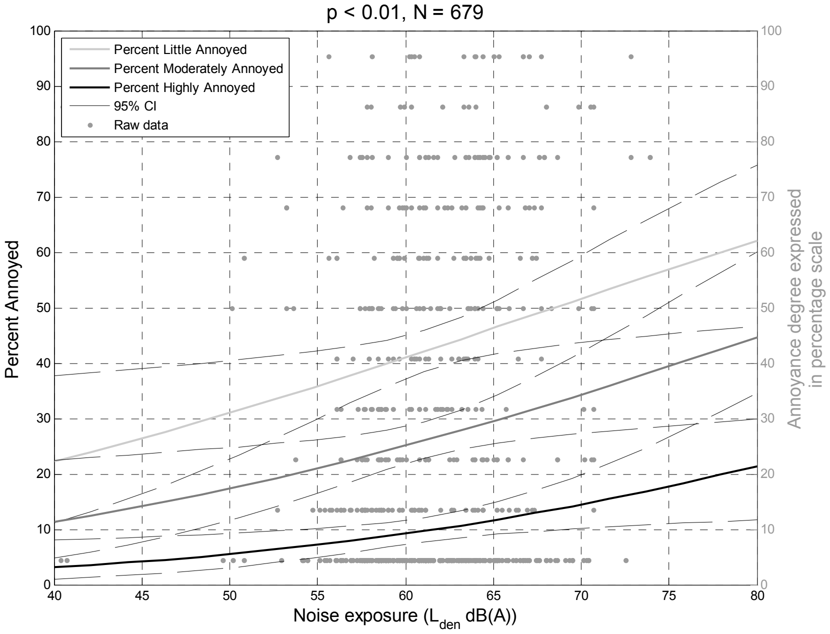

Figure 30. Percent little, moderately, and highly annoyed vs. noise exposure from railway with 95 % of confidence intervals. Annoyance measured via 11-point numeric scale.

Similar to Figure 27 and Figure 28, Figure 30 and Figure 31 illustrate the exposure-response relationship is plotted against the 11-point numeric scale along with scatter plot. The thresholds are defined in following way: %LA report any category higher than

"3"; %MA report any category higher than "5"; and %HA report any category higher than "7".

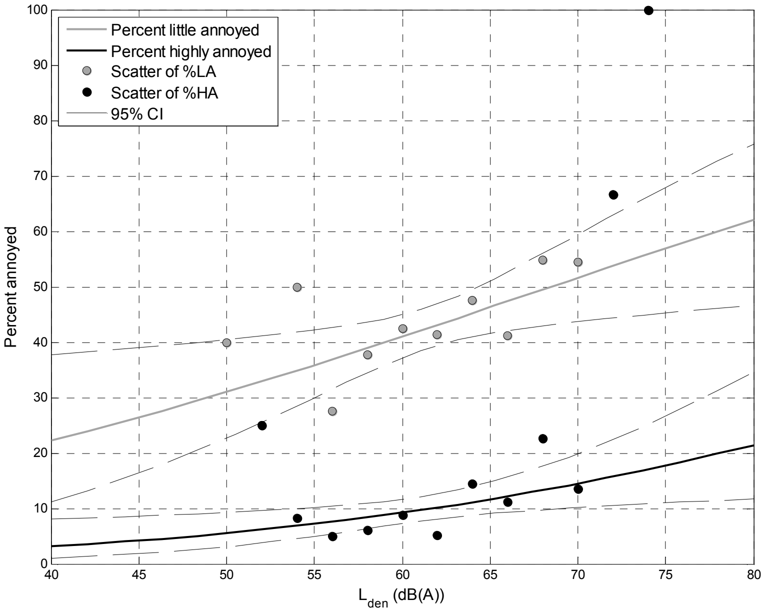

Figure 31. Percent little and highly annoyed vs. noise exposure from railway with scatter plot. Annoyance measured via 11-point numeric scale.

Figure 30 provide lower annoyance because of lower annoyance reported via this annoyance scale. Regarding the scatter, more points are concentrated at lowest annoyance categories. There is also a greater point spread according to Figure 31. Confidence Intervals are therefore very similar when both annoyance curves are compared. However, the scatter plot shows less the point spread of percent highly annoyed which is similar outcome to Figure 28.

Figure 27 and Figure 30 illustrate 95% CIs computed via and obtained from ordinal regression model; that is, based only on standard error. Due to assumption imposed, variations of estimated noise exposure are much wider and increased by errors from prediction. Hence, a greater point spread is expected and consequently higher wider confidence intervals.

It has been attempted to provide additional errors due to uncertainty evaluations (See section 4.8). The range of errors has been calculated elsewhere (See section 4.8) and turned to be ±10 dB(A). This is a maximal possible error caused by issues listed in the same chapter. Additional random errors has been added to L_{den} via rectangular probability distribution function of the amplitude ±10 dB(A). From this point, new confidence intervals were estimated and included around the same mean (Figure 32 and Figure 33) from Figure 27 and Figure 28.

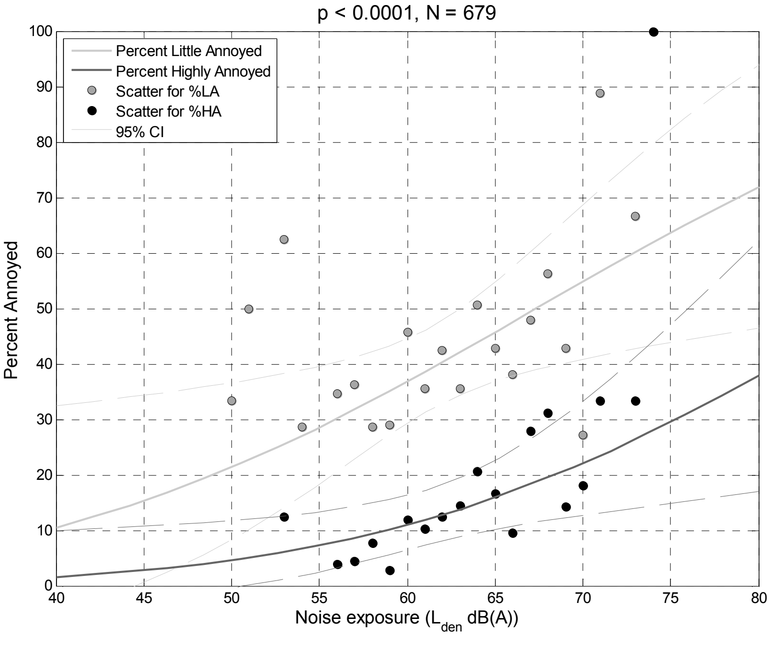

Figure 32. Percent little, moderately, and highly annoyed vs. noise exposure from railway with 95 % of confidence intervals including uncertainties evaluation (See section 4.8). Annoyance measured via 5-point semantic scale.

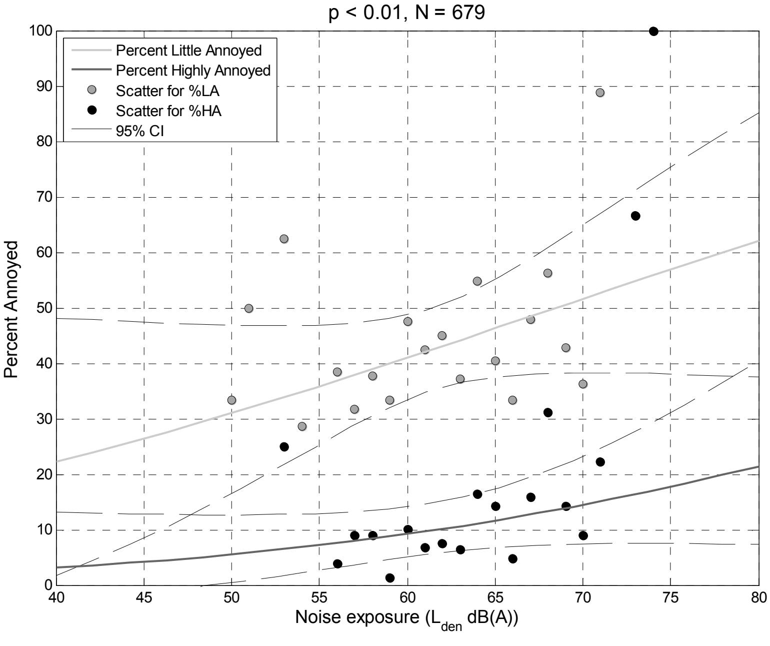

Figure 33. Percent little, moderately, and highly annoyed vs. noise exposure from railway with 95 % of confidence intervals including uncertainties evaluation (See section 4.8). Annoyance measured via 11-point numeric scale.

As the figures show, wider confidence intervals are an effect of a greater noise exposure and therefore wider fluctuations in exposure-response relationship.

5.3. INVESTIGATION OF COMBINED EFFECTS ON ANNOYANCE FROM NON-ACOUSTICAL VARIABLES

The main objective of this section is to present results from analysis of effects of non-acoustical factors on annoyance. Noise is found to be only partially contributing to annoyance. For instance, it has can be read that proportion of variance accounted for noise and annoyance was found to be not exceeding 20% (Job, 1988). Therefore analyses of additional factors were considered important for this project. The most important factor influencing annoyance is sleep disturbance (Fidell et al., 2000; Fields, 1993; Miedema et al., 1999; Öhrström et al., 2006). Before the results from analysis of this phenomenon is presented, the factors such as noise sensitivity, noise acceptance, distance, a number of events, age, and gender are first considered. Sleep disturbance as a single factor is then presented afterwards. Then, the relationship between sleep disturbance and separate factors such as noise sensitivity and noise acceptance are considered next. These factors have been analysed while controlled for noise exposure.

5.3.1. Noise sensitivity

During the field work, noise sensitivity was assessed via face to face interviews. Respondent were asked the following question:

The bar graph in Figure 34 has been included in results as noise sensitivity was found as fairly important factor influencing annoyance. Graph is drawn from reported categories while sensitivity was measure via social survey questionnaire. The left-hand side of the graph simply presents the subset of respondent reporting levels of sensitivity. On the other hand, right-hand side presents equivalent percentage scale.

The graph demonstrates that barely 1% (7) of people have reported to be “Extremely” sensitive, slightly less than 8% (65) reported “Very” sensitive, majority of people (52%, 431) answered to be “Not at all” followed by 23% (186) reporting to be “Slightly” sensitive. Two lowest categories cover over 75% (617) of participants. Due to the importance of noise sensitivity, this factor was also investigated with relationship to noise exposure and sleep disturbance.

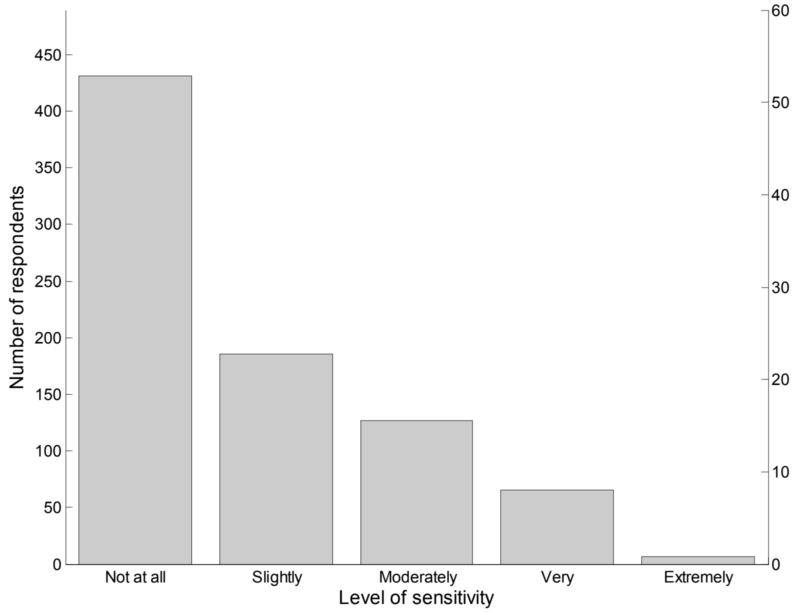

Figure 34. Distribution of people reporting noise sensitivity via 5-point semantic scale; N = 816.

How sensitive would you say you are personally to noise in general? Would you say you are not at all sensitive, slightly sensitive, moderately sensitive, very sensitive or extremely sensitive?

Ordinal regression model has been applied to analyse exposure-response relationship controlled for the third effect: noise sensitivity. It has been hypothesised that noise sensitivity may have slight influence on annoyance. Each graph in Figure 35, starting from upper left-hand side corner and going clockwise, represent exposure-response relationship at each level of noise sensitivity.

The outcomes demonstrate an influence on annoyance but it is not very strong. Even though exposure-response relationship slightly increases when higher levels of noise sensitivity are considered, the effect may be non-significant; that is, solid lines change but only within confidence intervals. Therefore, it has to be concluded from this findings that noise sensitivity has not very strong influence based on existing dataset.

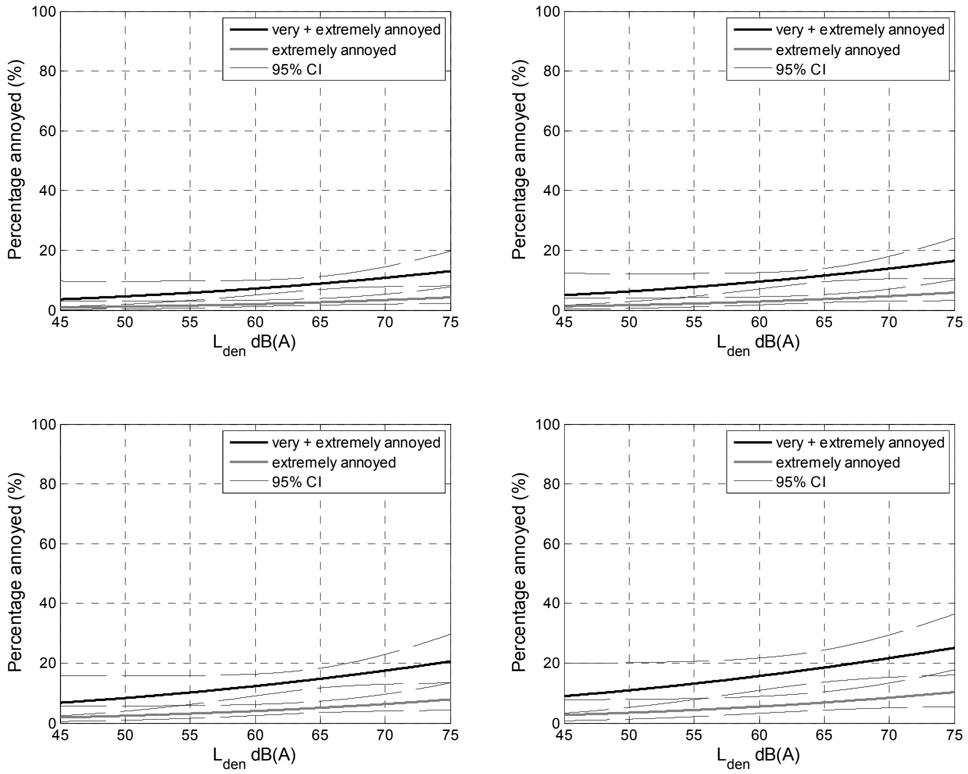

Figure 35. Proportion of respondents reporting annoyance levels "very" + "extremely" and “extremely” controlling for each level of noise sensitivity: "not at all", "slightly", "moderately", and "very" (clockwise).

5.3.2. Distance

Figure 36 shows the relationship between a distance and percent highly annoyed. For the Figure 36, this factor has not been controlled for the third variable. It illustrates the changes in reported annoyance when respondent is at greater distance to the noise source. The effect has been found to be significant ($p < 0.0001$). Relatively low Spearman’s correlations between the distance and both annoyance scales were found. As such, correlation between the distance and 5-point semantic scale was found to be $\rho_S = -0.142$ ($p<0.0001$). On the other hand, correlation between the distance and 11-point numeric scale was found to be $\rho_S = -0.127$ ($p < 0.0001$). These numbers express correlations when noise exposure was neglected.

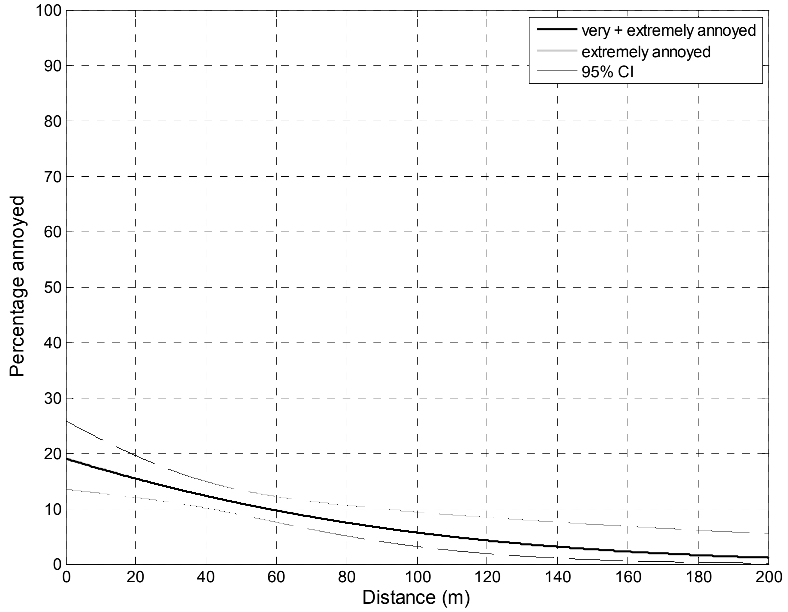

Figure 36. Percentage of people reporting to be "very" + "extremely" and "extremely" annoyed ($p < 0.005$, $R^2=0.005$).

To investigate this factor more thoroughly, the noise exposure has been split into four groups. Table 18 contains the results from analyses of percent highly annoyed given the distance while variables are controlled for noise exposure.

Table 18. Spearman's correlation between two annoyance scales and noise distance controlled for noise exposure

		Noise level in dB(A)			
		40–50	**50-60**	**60-70**	**70-80**
Correlation	5-p. sem. scale vs. dist.	-0.095**	-0.118*	-0.100*	-0.285**
	11-p. num. scale vs. dist.	-0.275**	-0.100*	-0.108*	-0.288**
	N - number of respondents	11	291	419	20

* $p < 0.05$; ** $p > 0.05$

Relatively low numbers have been obtained considering the each noise category. It may be concluded that this effect is not interacting with level of noise exposure because Spearman's correlations do not vary in corresponding categories. The correlation is also non-significant for categories 40-50 dB(A) and 70-80 dB(A) but this may be caused by a very low number of cases within those groups. Spearman's correlations confirm the effect of distance on proportion of highly annoyed illustrated by the Figure 36. When greater the distance from railway, the lower is proportion of highly annoyed.

The correlation between level of noise and the distance was found to be -0.412. It is important to mention though that noise was predicted and the distance was the main factor. Consequently, this correlation has to be found strong.

5.3.3. Age

Age is an important factor with regarding to annoyance (Miedema et al., 1999). It has been found that effect of age against percent highly annoyed has a U-shape inverse relationship. Figure 37 illustrates changes in annoyance fitted by a quadratic function. Figure 38, on the other hand, shows the curved fitted via fractional polynomial[8] curve. The details about this method are explained in papers by Royston et al. (1994), Royston et al. (1999), and Royston et al. (2004). The curve in Figure 38 shows the relationship between %HA and age. The variable age is grouped in categories: 15-25, 25-35, ... 75-85. The proportion of highly annoyed has been calculated within each category.

Both figures (Figure 37 and Figure 38) predict maximum annoyance at the middle age between 40-50 years. The same relationship is illustrated by Figure 39 while %HA are considered based on 11-point numeric scale.

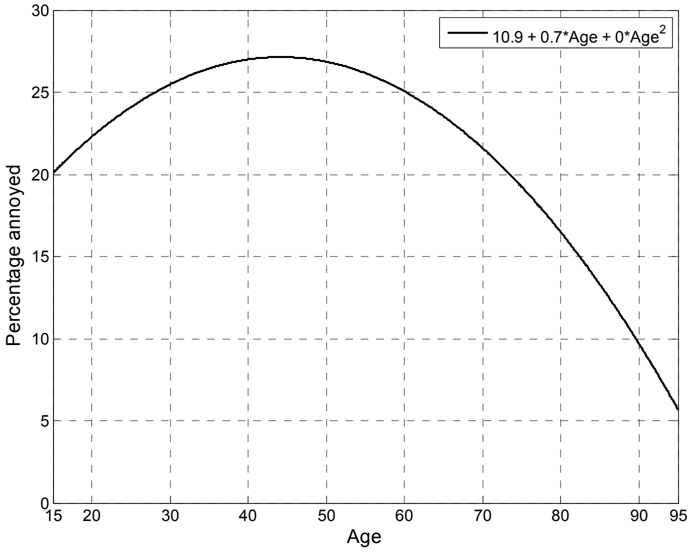

Figure 37. Effect of age on annoyance. Standard quadratic was applied to fit the curve.

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[8] Fractional Polynomial models stems from fractional polynomial equations which are more general case of polynomial equation and contain fractional numbers at their variables

Table 19 contains descriptive statistics regarding the variable age. The mean of all respondents is around an age of 50.

Table 19. Statistics for age of respondents exposed to railway noise

Mean	Std. Deviation	Range	Minimum	Maximum
48.6	18.6	78	16	94

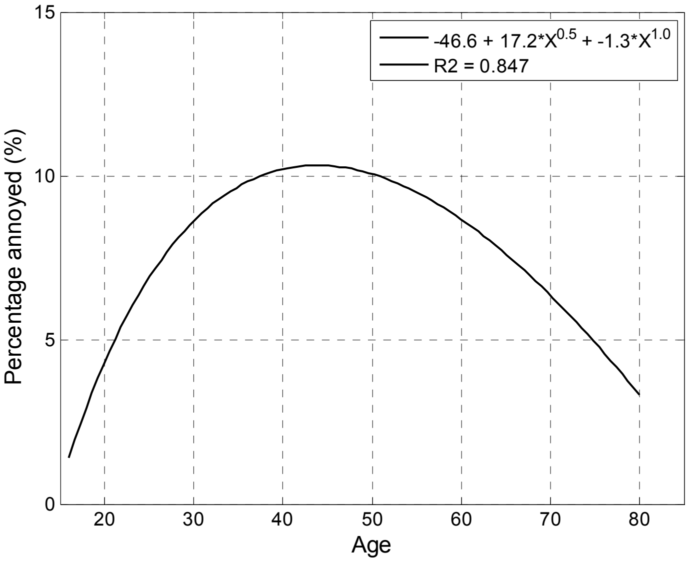

Figure 38. Curve fitting for the effect of age on annoyance measured in 5 point scale via fractional Polynomial.

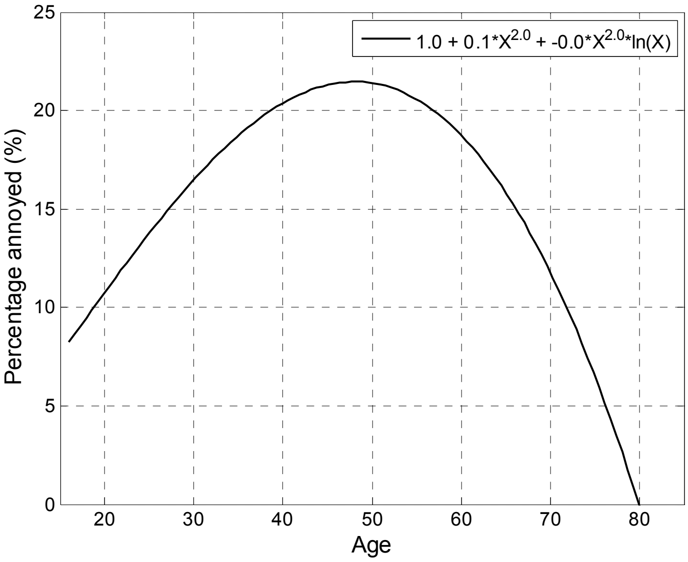

Figure 39. Curve fitting for the effect of age on annoyance measured in 11 point scale via fractional Polynomial.

The figures confirm annoyance is dependant of the factor age. Similarly to the outcome in this work, relatively young and relatively old persons are less annoyed. Fields (1993), on the other hand, did not find clear evidence that age has an effect on annoyance, though. The reason may at least partially lie behind the fact that many studies included in the analysis only investigated the existence of linear relationship between annoyance and age (Miedema et al., 1999).

The effect has been found significant and clear based on Figure 37, Figure 38, and Figure 39. Two different fits and two annoyance scales provider evidence of the effect of age on annoyance. There is not clear explanation why relatively old and relatively young people report less annoyance.

The article by Hilton et al. (2008) provides information on age and percentage of people who suffer from Age-Related Hearing Loss (ARHL). Prevalence of hearing loss in people of age over 50 years is estimated at 50% and in those older than 80 as being 90% (Huang, 2007). Relatively older people might also get used to circumstances they were to live for years. In terms of relatively younger people, it is hypothesised that probably the best explanation for reporting less annoyance is that younger persons may not see the problem and therefore do not feel disturbed.

5.3.4. Gender

Histogram presented by Figure 40 is a simple relationship between gender and 5-point annoyance scale.

This figure is to provide information with regard to an effect of gender on annoyance. The graph was produced from social survey questionnaire while reported annoyance is controlled for gender. It shows two histograms corresponding to two groups of respondent Male and Female. Although it may not be clear by the first inspection, two histograms show similar relationships between bars within each groups of Male and Female.

If the interaction existed, then graph would provide two different relationships between categories within each group. This finding is in accordance to literature where Fields (1993) also did not find gender an influential factor on annoyance.

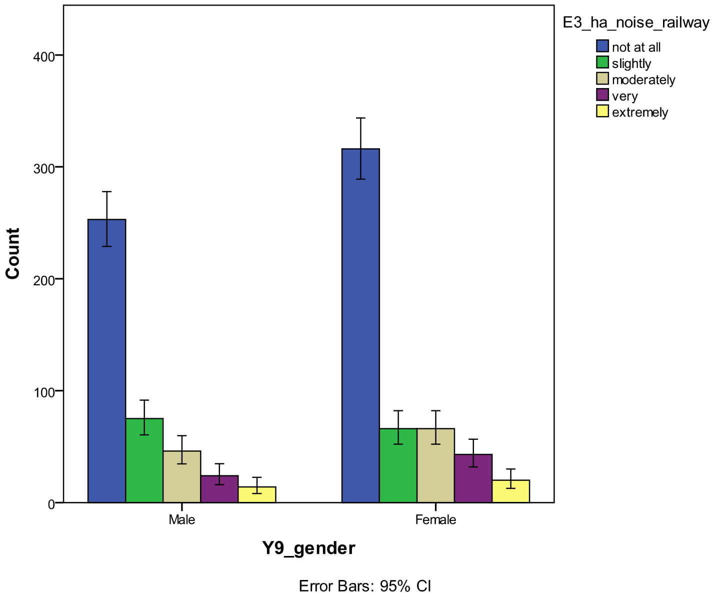

Figure 40. The histogram of relationship between gender and annoyance level.

To support the conclusion from observation of the Figure 40, Mann-Whitney test has been conducted. Mann-Whitney is a statistic test similar to t-student that determines whether a variable has the same effect on two groups and returns null hypothesis. The test has revealed that null hypothesis is true (p-value equal to 0.8330 > 0.05). In conclusion, there is no a significantly different effect of gender on annoyance.

5.4. SLEEP DISTURBANCE

This section provides information with regard to sleep disturbance that occurring while residents are affected by noise from railway. First, sleep disturbance is considered as a single effect during noise events occurring at night-time period. Then, considerations of other potentially influential factors are presented in further sections. The other factors such as noise sensitivity and noise acceptance could be the reason of a greater complaining and consequently reporting higher proportion of annoyed.

5.4.1. Sleep disturbance versus annoyance controlled for noise exposure

Sleep disturbance was assessed via face to face interviews. The following question from social survey questionnaire has been asked:

"Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by hearing noise caused by railway? Would you say not at all, slightly, moderately, very or extremely?"

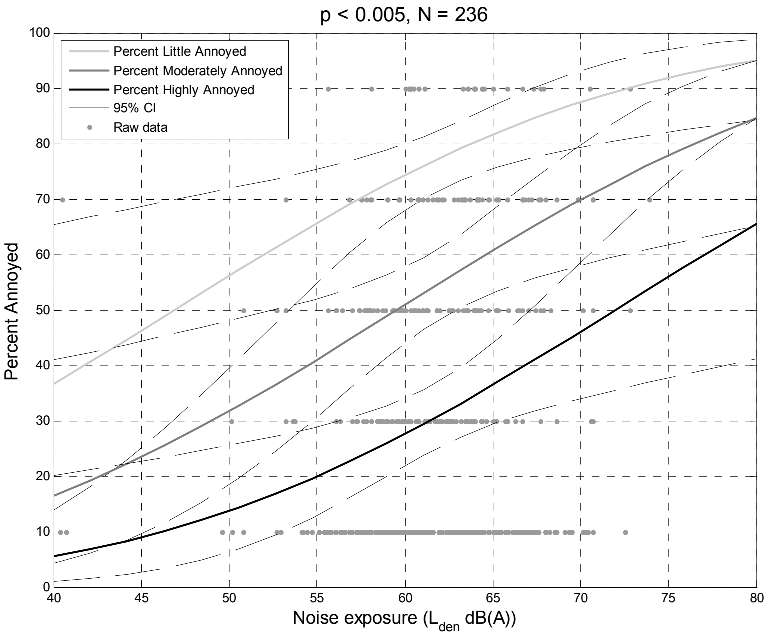

Figure 41. Percent annoyed reporting sleep disturbance. A number of cases is equal to 236 (34.8%) out of 679 ($p < 0.005$, $R^2 = 0.0116$). Noise exposure is drawn applying 5-point semantic scale.

Figure 41 shows percentage of people who reported to be little, moderately, and highly annoyed considering participants disturbed at night-time period. The wider confidence intervals resulted from taking the subset of cases and consequently a lower number of data was provided for the analysis. The most important conclusion from this graph is that reported annoyance is significantly higher by participants who simultaneously report sleep disturbance.

Table 20 contains cross-product between reported annoyance levels and sleep disturbance controlled for each noise level categories. The last group of four columns contains results from analyses of odds ratios. This statistic compares fours cells as follows: two columns of the 5-point semantic scale are compared with two rows of the sleep disturbance. If any of these cells is greater than one, then it suggests higher likelihood that sleep disturbance occurs while higher level of annoyance is reported. The category "Not at all" is considered as a reference. Each odds ratio is calculated with respect to this category.

Considering the group called "50-60 dB(A)" in the Table 20, it can be seen that odds ratios increase while annoyance increases. Categories “Very” and “Extremely” are defined as percent highly annoyed. Therefore, it can be concluded that for this noise level category annoyance increases while sleep disturbance occurs. In the group called

"50-60 dB(A)", the odds ratios between third and first annoyance categories is 7.93. It is about 8 times more likely that, when respondents are disturbed at night-time period, respondents will report to be "moderately" annoyed (category “3”).

The last groups of rows "Total" contains all summarized counts from each noise categories. Odds ratios calculated for this row indicates a trend when variables are not controlled for noise exposure. In other words, an effect of noise exposure on both variables is neglected. It can be observed that, for this group of rows, the odds ratios increase. The last two cells contain the numbers 19.12 and 20.58. They indicate that reported high annoyance is roughly 20 times more likely if sleep disturbance is reported.

Table 20. The contingency table shows a number of respondents simultaneously reporting each category of sleep disturbance, level of noise exposure, and annoyance level. The table presents Odds Ratios.

Lden /dB(A)			**5-point semantic scale**					**Total**	**Odd Ratios**			
			1	**2**	**3**	**4**	**5**		**2/1**	**3/1**	**4/1**	**5/1**
40-50	**Sleep disturbance**	**no**	7.5	1.5	0.5	1.5	0.5	11.5	1.67	5.00	1.67	5.00
		yes	1.5	0.5	0.5	0.5	0.5	3.5				
	Total		9.0	2.0	1.0	2.0	1.0	15.0				
50-60	**Sleep disturbance**	**no**	178.5	33.5	20.5	5.5	3.5	241.5	4.38	7.93	13.70	7.93
		yes	22.5	18.5	20.5	9.5	3.5	74.5				
	Total		201.0	52.0	41.0	15.0	7.0	316.0				
60-70	**Sleep disturbance**	**no**	212.5	33.5	20.5	10.5	4.5	281.5	6.95	11.68	24.74	29.23
		yes	31.5	34.5	35.5	38.5	19.5	159.5				
	Total		244.0	68.0	56.0	49.0	24.0	441.0				
70-80	**Sleep disturbance**	**no**	7.5	3.5	3.5	1.5	0.5	16.5	2.14	0.71	8.33	25.00
		yes	1.5	1.5	0.5	2.5	2.5	8.5				
	Total		9.0	5.0	4.0	4.0	3.0	25.0				
Total	**Sleep disturbance**	**no**	406.0	72.0	45.0	19.0	9.0	541.0	5.44	9.02	19.12	20.58
		yes	57.0	55.0	57.0	51.0	26.0	236.0				
	Total		463.0	127.0	102.0	70.0	35.0	797.0				

The row with digits 1, 2, 3, 4, and 5 correspond to level of annoyance in 5-point semantic scale: 1 – "not at all", 2 – "slightly", 3 – "moderately", 4 – "very", 5 – "extremely".
2/1 ... 5/1 – expresses odds ratios between following categories: "slightly" and "not at all" ... "extremely" and "not at all"; "not at all" takes a sort of control group in these investigations

Table 21 shows descriptive statistics testing association of two variables sleep disturbance and annoyance, while influence of the third variable noise exposure is considered. Only two noise categories are taken into account because of cells containing 0 counts in other categories. As can be seen, variables sleep disturbance and 5-point semantic scale controlled for two categories of noise exposure reveal mutual dependence (Chi-squared statistics); that is, changes of sleep disturbance from not disturbed to disturbed are in accordance with changes of annoyance levels from lower to higher categories; or, in other words, one variable does not change randomly with respect to the other. Additionally, the last row "Total" shows all statistics when sleep disturbance and annoyance are not controlled for noise exposure--counts due to number of people in particular noise exposure categories is summarized and therefore neglected.

In both cases, the results from statistics confirm interaction between sleep disturbance and annoyance in association with noise exposure. Sleep disturbance does not occur randomly but has its clear effect on annoyance.

Table 21. Statistics based on Table 20.

	Nominal independence (Chi-squared tests)		Nominal Association			Ordinal Association		
	Pearson's	likelihood ratio	Pearson's	Cramer's V	Spearman's rho	Gamma	Kendall's τ_b	Kendall's τ_c
50-60	49.71^{*}	52.78^{*}	0.381	0.412	0.407^{*}	0.668^{*}	0.386^{*}	0.338^{*}
60-70	148.9^{*}	142^{*}	0.496	0.571	0.570^{*}	0.778^{*}	0.529^{*}	0.572^{*}
Total	204.7^{*z}	203	0.452	0.507	0.505^{*}	0.730^{*}	0.471^{*}	0.480^{*}

$p < 0.0001$

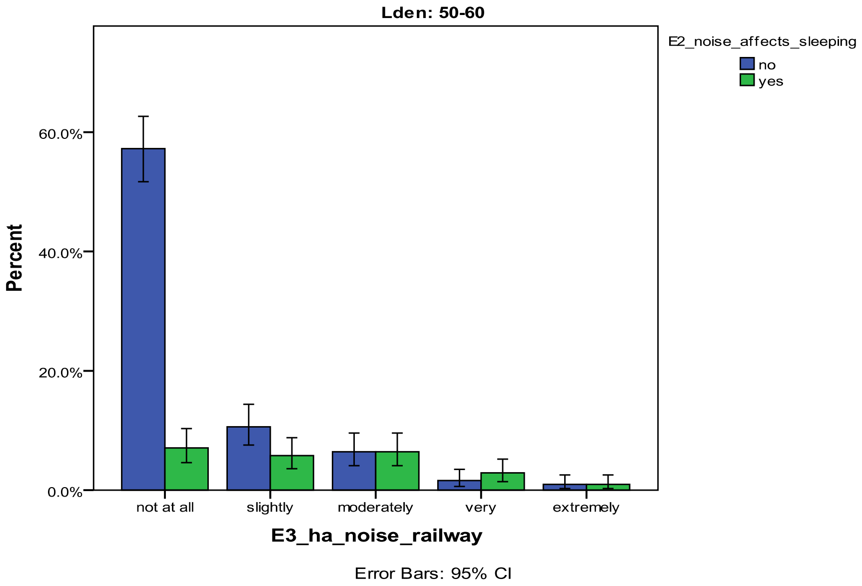

Figure 42. The histogram showing sleep disturbance affection changes due to noise level of 50-60 dB(A) with an increase of annoyance.

This is important outcome because it suggests that greater proportion of highly annoyed can be expected by reason of sleep disturbance. In conclusion, it could be hypothesised that noise level could be reduced to the lowest possible level that would not disturb residents at night-time period.

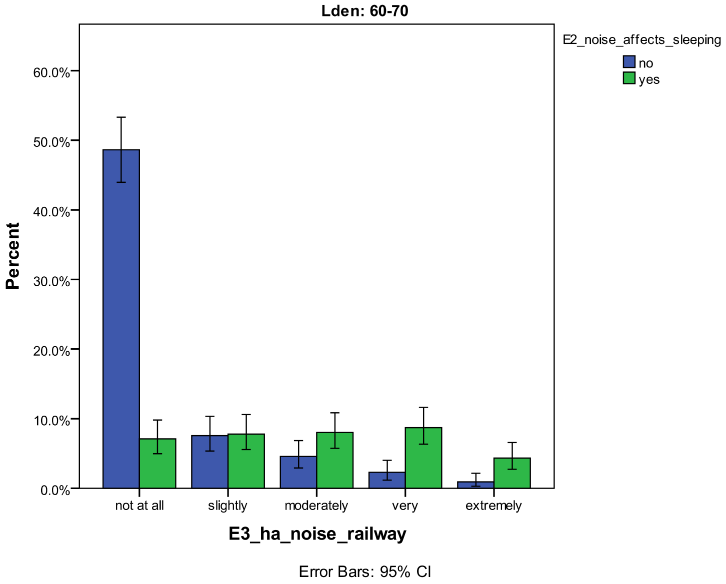

Figure 43. The histogram showing sleep disturbance affection changes due to noise level of 60-70 dB(A) with an increase of annoyance.

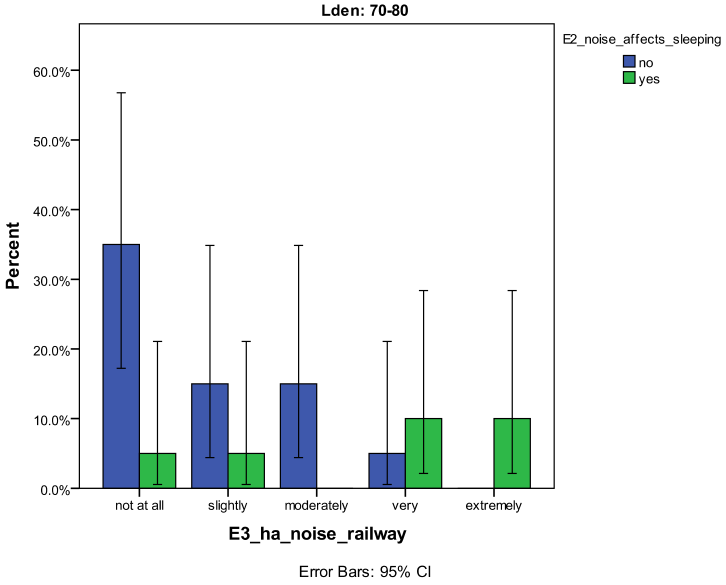

Figure 44. The histogram of sleep disturbance changes due to noise level of 70-90 dB(A) with an increase of reported sensitivity.

5.4.2. Interaction between sleep disturbance and sensitivity controlled for noise exposure

In this section, annoyance is exchanged with noise sensitivity. The interaction between sensitivity and sleep disturbance is not strongly pronounced, besides the group of participants reporting to be "extremely" annoyed (in 5-point semantic scale). However, results from analysis of noise sensitivity have been provided in one of the previous sections. In conclusion, the noise sensitivity has not a significant effect on annoyance.

From Table 22, odds ratios are calculated in similar way to odds ratios in previous section. The category “Not at all” is the reference. The other categories are calculated with respect to this one.

There is the little difference between compared categories while respondents are disturbed during asleep or they are not. Also from Figure 45, Figure 46, and Figure 47, the same conclusion can be drawn. The proportions between disturbed and not disturbed given noise exposure 50-60 dB(A) does not seem to differ between category "not at all" and any other category etc. Another way of reading this is to look at correlations between variables. In section (5.3.1) it has been found that correlation between annoyance and sensitivity is poor.

The similar considerations supporting outcomes based on Table 22 can be found in Table 23. The effect between noise sensitivity and sleep disturbance controlled for two noise exposure categories can be observed. The chi-squared test does not reveal dependence, suggesting that noise sensitivity does not change in accordance with sleep disturbance. However, three last statistics such as Gamma, Kendall’s τ_{b}, and Kendall’s τ_{c}, show significant association taking into account an ordinal characteristic of both variables. The association is not as strong as the one considering sleep disturbance and annoyance, though. From these outcomes, one can expect slight increases in annoyance when higher noise sensitivity is reported. When a noise effect on variables is neglected (last row with statistics), then the relationship between two variables is a slightly weaker. It is important to mention that variables are ordinal and positive sign of ordinal association suggest that positive changes in both variables.

Table 22. The contingency table showing frequency distribution between following categorical data and odds ratios: sleep disturbance, level of noise exposure, and noise sensitivity.

Lden_interval_10dB			**E5_how_sensitive_to_noise**					**Total**	**Odd Ratios**			
			1	2	3	4	5		2/1	3/1	4/1	5/1
40-50	E2_noise_affects_sleeping	no	4.5	3.5	1.5	1.5	0.5	11.5	3.9	3.0	3.0	9.0
		yes	0.5	1.5	0.5	0.5	0.5	3.5				
	Total		5.0	5.0	2.0	2.0	1.0	15.0				
50-60	E2_noise_affects_sleeping	no	122.5	70.5	25.5	19.5	0.5	238.5	1.2	2.1	1.8	12.0
		yes	30.5	20.5	13.5	8.5	1.5	74.5				
	Total		153.0	91.0	39.0	28.0	2.0	313.0				
60-70	E2_noise_affects_sleeping	no	153.5	54.5	50.5	17.5	2.5	278.5	1.3	1.5	1.9	3.9
		yes	70.5	33.5	34.5	15.5	4.5	158.5				
	Total		224.0	88.0	85.0	33.0	7.0	437.0				
70-80	E2_noise_affects_sleeping	no	6.5	3.5	3.5	2.5	0.5	16.5	1.3	0.3	1.1	1.9
		yes	3.5	2.5	0.5	1.5	0.5	8.5				
	Total		10.0	6.0	4.0	4.0	1.0	25.0				
Total	E2_noise_affects_sleeping	no	287.0	132.0	81.0	41.0	4.0	541.0	1.2	1.7	1.7	4.8
		yes	105.0	58.0	49.0	26.0	7.0	236.0				
	Total		392.0	190.0	130.0	67.0	11.0	790.0				

The row with digits 1, 2, 3, 4, and 5 correspond to level of sensitivity in 5-point semantic scale: 1 – "not at all", 2 – "slightly", 3 – "moderately", 4 – "very", 5 – "extremely".

2/1 ... 5/1 – expresses odds ratios between following categories: "slightly" and "not at all" ... "extremely" and "not at all"; "not at all" takes a sort of control group in these investigations

Table 23. Statistics based on Table 22.

	Nominal independence (Chi-squared tests)		Nominal Association			Ordinal Association		
	Pearson's	likelihood ratio	Pearson's	Cramer's V	Spearman's rho	Gamma	Kendall's τ_b	Kendall's τ_c
50-60	6.98**	7.55**	0.155	0.157	0.110*	0.206*	0.103*	0.100*
60-70	6.86**	7.01**	0.126	0.127	0.115*	0.191*	0.107*	0.117*
Total	12.6*	13.2*	0.129	0.113	0.111*	0.189*	0.103*	0.109*

* - $p < 0.05$, ** $p > 0.05$

Similar to analysis in one of the previous section (5.3.1), noise sensitivity this factor has not been found to be strongly influential. In ca be concluded from existing dataset that noise sensitivity was found a non-influential factor on annoyance regardless of additional effect such as sleep disturbance.

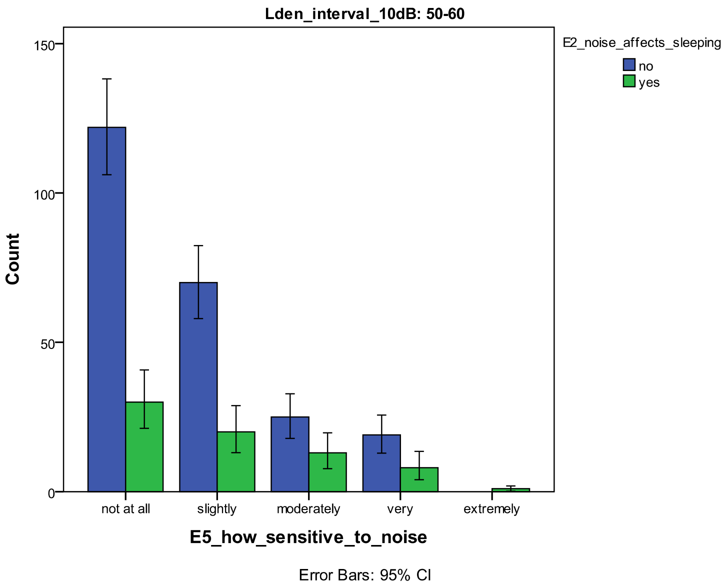

Figure 45. The histogram of changed of sleep disturbance changes due to noise level of 50-60 dB(A) with an increase of reported sensitivity.

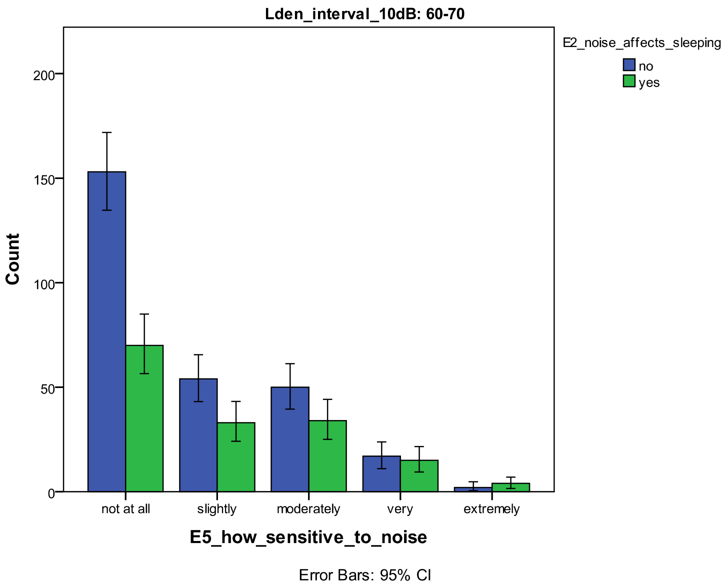

Figure 46. The histogram of changed of sleep disturbance changes due to noise level of 60-70 dB(A) with an increase of reported sensitivity.

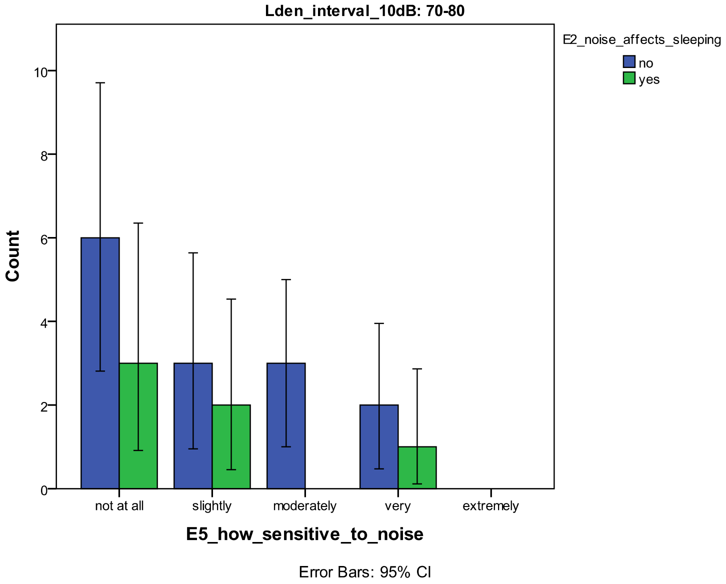

Figure 47. The histogram of changed of sleep disturbance changes due to noise level of 70-80 dB(A) with an increase of reported sensitivity.

5.4.3. Interaction between sleep disturbance, acceptance of noise, and noise exposure

In this section, interaction between sleep disturbance and acceptance of noise given a level of noise exposure is investigated. Similarly to annoyance and sensitivity to noise, acceptance was measured by 5-point semantic scale, but category names changed into following: "very acceptable", "acceptable", "neither", "unacceptable" and "very unacceptable".

Looking at this scale [show card 6] and given all that you have said, over the last 12 months or so, how acceptable have you found the level of noise you have experienced in this home. Would you say it has been very acceptable, acceptable, neither acceptable nor unacceptable, unacceptable or very unacceptable?

In Table 24, a group of respondents reported category "neither" was found most adequate for a reference group. A proportion between respondents affected by noise during asleep is different: for categories "very acceptable" and "acceptable" a majority of people answered "No"; for categories "unacceptable" and "very unacceptable", a majority of people answered "Yes". Similarly to the figures, Table 24 also presents data utilizing counts and Odds Ratios.

Two categories have been compared: “Neither” and “Very acceptable”. It has been found that 2.33 times more people report category “Neither” than category “Very acceptable” if they feel disturbed at night. Similarly, the cell in the groups of odds ratios containing the number of 5.97 demonstrates that almost six times more people report category “Unacceptable” than “Neither” when sleep disturbance occurs.

Following the conclusion from Table 24 and figures (Figure 48, Figure 49, and Figure 50), there is an interaction between acceptance of noise and sleep disturbance. As noise is more acceptable, so is reduced number of sleep disturbances as well. This effect rapidly changes (columns "4/3" and "5/3") when categories "unacceptable" and "very unacceptable" are considered. It can expected that people in dwellings would express less noise acceptance when the sleep disturbance is the problem. This indicates that sleep disturbance is also associated with acceptance of noise meaning that the less accepted noise level, the greater is probability of reporting sleep disturbance.

Table 25 presents descriptive statistics regarding sleep disturbance effect on noise acceptance while both variables are controlled for noise exposure. Much stronger association between sleep disturbance and noise acceptance is revealed comparing to noise sensitivity. Noise acceptance is an ordinal variable whose levels are of higher ranks when effect is stronger. Therefore, ordinal association statistics are positive suggesting strong positive relationships between noise acceptance and sleep disturbance controlled for noise exposure. The last row contains statistics when two variables are not controlled for noise exposure. Even though, the effect still exists. It can therefore be confirmed that noise acceptance has an effect on sleep disturbance regardless of noise exposure.

In conclusion, when noise is reported to be not acceptable, it is more likely that sleep disturbance is reported.

Table 24. The contingency table showing frequency distribution between following categorical data and odds ratios: sleep disturbance, level of noise exposure, and acceptance of noise.

Lden_interval_10dB			**E6_acceptable_noise**					**Total**	**Odd Ratios**			
			1	2	3	4	5		3/1	3/2	4/3	5/3
40-50	E2_noise_affects_sleeping	no	3.5	4.5	1.5	1.5	0.5	11.5	2.33	1.00	1.00	3.00
		yes	0.5	1.5	0.5	0.5	0.5	3.5				
	Total		4.0	6.0	2.0	2.0	1.0	15.0				
50-60	E2_noise_affects_sleeping	no	66.5	143.5	19.5	10.5	0.5	240.5	20	4.54	1.48	9.00
		yes	3.5	31.5	19.5	15.5	4.5	74.5				
	Total		70.0	175.0	39.0	26.0	5.0	315.0				
60-70	E2_noise_affects_sleeping	no	61.5	184.5	26.5	5.5	1.5	279.5	16.7	3.12	5.97	2.90
		yes	4.5	73.5	33.5	41.5	5.5	158.5				
	Total		66.0	258.0	60.0	47.0	7.0	438.0				
70-80	E2_noise_affects_sleeping	no	1.5	13.5	0.5	0.5	0.5	16.5	9.1	11.1	1.67	0.33
		yes	0.5	3.5	1.5	2.5	0.5	8.5				
	Total		2.0	17.0	2.0	3.0	1.0	25.0				
Total	E2_noise_affects_sleeping	no	133.0	346.0	48.0	18.0	3.0	541.0	0.06	0.28	2.91	3.20
		yes	9.0	110.0	55.0	60.0	11.0	236.0				
	Total		142.0	456.0	103.0	78.0	14.0	793.0				

The row with digits 1, 2, 3, 4, and 5 correspond to level of acceptance in 5-point semantic scale: 1 – "very acceptable", 2 – "acceptable", 3 – "neither",4 – "unacceptable", 5 – "very unacceptable".

1/3, 2/3, 4/3, and 5/3 – expresses odds ratios between following "neither" and all the other categories

Table 25. Statistics based on Table 24.

	Nominal independence (Chi-squared tests)		Nominal Association			Ordinal Association		
	Pearson's	likelihood ratio	Pearson's	Cramer's V	Spearman's rho	Gamma	Kendall's τ_b	Kendall's τ_c
50-60	64.95*	64.11*	0.414	0.455	0.417*	0.732*	0.391*	0.366*
60-70	111.2*	103.2*	0.44	0.49	0.469*	0.758*	0.44*	0.469*
Total	170*	168*	0.419	0.462	0.442*	0.729*	0.414*	0.421*

* - $p < 0.0001$

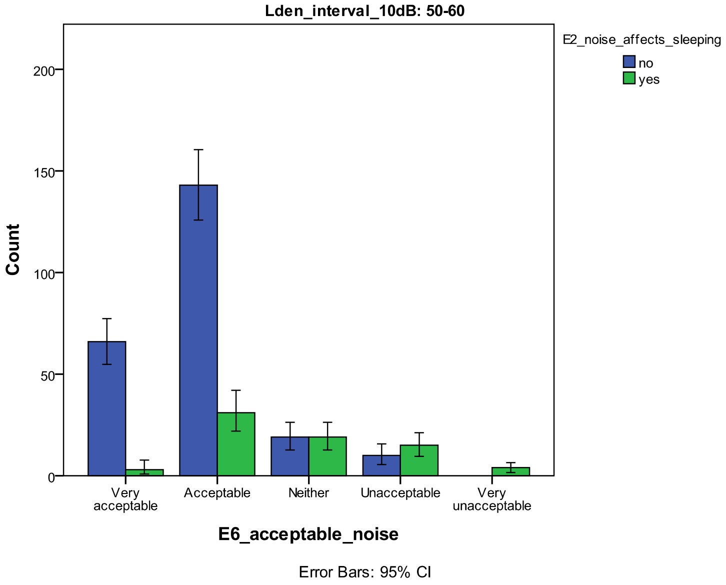

Figure 48. The histogram of changed of sleep disturbance due to noise level of 50-60 dB(A) with an increase of reported acceptance.

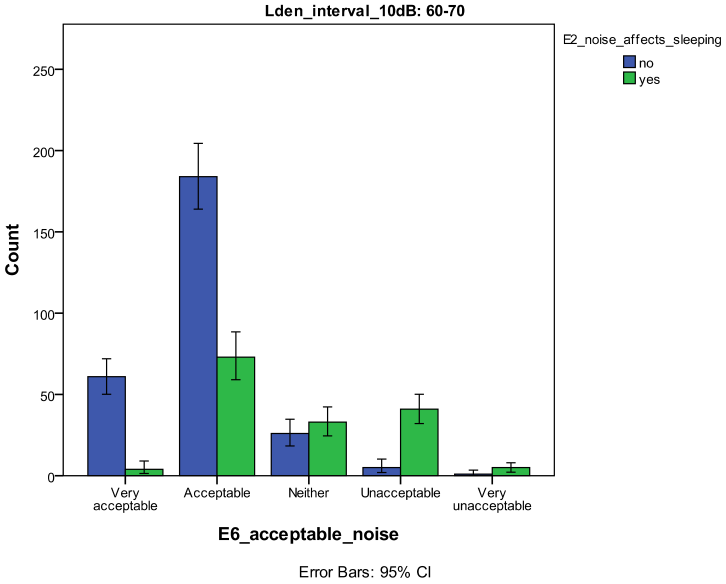

Figure 49. The histogram of changed of sleep disturbance due to noise level of 60-70 dB(A) with an increase of reported acceptance.

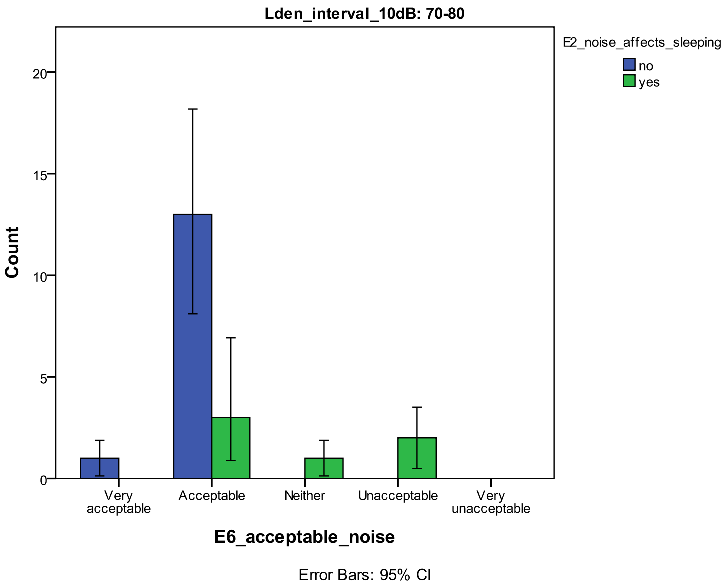

Figure 50. The histogram of changed of sleep disturbance due to noise level of 70-80 dB(A) with an increase of reported acceptance.

5.5. EXPOSURE-RESPONSE RELATIONSHIP TO VIBRATION

This section provides discussion on exposure-response relationship to vibration. The results have been based on two vibration metrics: $VDV_{b,24h}$ $(m/s^{-1.75})$ and RMS W_k (m/s^2). The curves represent thresholds determining percent little annoyed, percent moderately annoyed, and percent highly annoyed. The thresholds are separately defined with respect to two independent response measures: 5-point semantic scale and 11-point numeric scale. As such, additional graphs illustrate exposure-response relationship to vibration by illustrating application of these two measures.

The section also provides information on changes of percentage of highly annoyed during the periods of day-time and night-time, although such metrics have not been included in this project. Therefore, latter outcomes are presented only for the informative purpose.

In the last part, there is a discussion on sleep disturbance occurrence while the vibration exposure takes place.

5.5.1. Relationship between vibration exposure and annoyance

Similarly to noise exposure (See section 5.2), Figure 51 illustrates exposure-response relationship to vibration expressed by $VDV_{b,24h}$. Annoyance is measured via 5-point semantic scale. Figure 53 is similar to Figure 51 but annoyance is measure via 11-point numeric scale. Figure 52 and Figure 54 show scatter plots on the top of the curves from Figure 51 and Figure 53. The scatter was obtained by taking intervals of 1 dB (re 1 $VDV_{b,24h}$ ($ms^{-1.75}$)) and then proportion between the whole subset and those reporting little or highly annoyed from this subset was calculated.

Figure 56 and Figure 58 illustrate exposure-response relationship to vibration using RMS W_k. Figure 57 and Figure 59 show scatter plots on the top of annoyance curves. The scatter was also obtained by taking intervals of 1 dB (re 1 RMS W_k (ms^{-2})) and then proportion between subset and little or highly annoyed from this subset was calculated.

Each figure can be compared with Figure 55 that shows probability of feeling vibration from railway. The proportion of highly annoyed (around 18%) for maximal predicted vibration in $VDV_{b,24h}$ corresponds to 99% of participants reporting feeling vibration. At the point of 50% of feeling vibration (around $VDV_{b,24h} = 8^{x}10^{-3}$ $m/s^{1.75}$), about 7% reported to be highly annoyed. Percentage of annoyed becomes greater when a number of participants feeling vibration increases. Also, the higher vibration exposure, the greater is percentage of annoyed.

The Table 26 and shows probability of adverse comments for given vibration exposure based on suggestions from (BS ISO 6472-1:2008, 2008) and (ANC Guidelines, 2001). Probabilities are grouped with respect to time periods such as day and night. The table utilizes two vibration indices such as $VDV_{b,day}$ and $VDV_{b,night}$, which were not included in analyses conducted for this project. It is not clearly stated what is meant by "adverse comment". Therefore it is difficult to assess the application of this guidance.

For the limits provided by Table 26, Woodcock, Waddington, et al. (2011) provided proportion of respondents reporting high annoyance regarding vibration exposure.

Vibration exposure is indicated by both $VDV_{b,day}$ during day-time and $VDV_{b,night}$ during night-time. As expected, when vibration exposure is stronger a number of reporting high annoyance increases. Similar to noise exposure, the effect is greater during the night-time period. This is confirmed in paper by Peris et al. (2012) who has investigated how proportion of highly annoyed changes at different time periods and concluded that the highest number of people reporting high annoyance can be expected at night time periods.

Table 26. Probability of adverse comment for a range of vibration exposures as suggested in BS 6472-1:2008. Values provided in the ANC guidelines are shown in brackets (Woodcock, Waddington, et al., 2011).

Place and time	**Low probability of adverse comment m/s1.75**	**Adverse comment possible m/s1.75**	**Adverse comment probable2 m/s1.75**
Residential buildings 16hr day	0.2 – 0.4	0.4 – 0.8	0.8 – 1.6
Residential buildings 8hr night	0.1 – 0.2(0.13)	0.2 – 0.4 (0.26)	0.4 – 0.8 (0.51)

Table 27. Percentage of respondents expressing high annoyance for vibration exposure in the limits provided in Table 2. (* - outside range of measured exposures) (Woodcock, Waddington, et al., 2011).

Exposure	< 0.2 $VDV_{b,day}$	0.2 – 0.4 $VDV_{b,day}$	0.4 – 0.8 $VDV_{b,day}$	0.8 – 1.6 $VDV_{b,day}$	> 1.6 $VDV_{b,day}$
%HA Railway	0 – 3	3 – 4	> 4 *	> 4 *	> 4 *
Exposure	< 0.1 $VDV_{b,night}$	0.1 – 0.2 $VDV_{b,night}$	0.2 – 0.4 $VDV_{b,night}$	0.4 – 0.8 $VDV_{b,night}$	> 0.8 $VDV_{b,night}$
%HA Railway	0 – 12	12 – 15	15 – 19	> 19 *	> 19 *

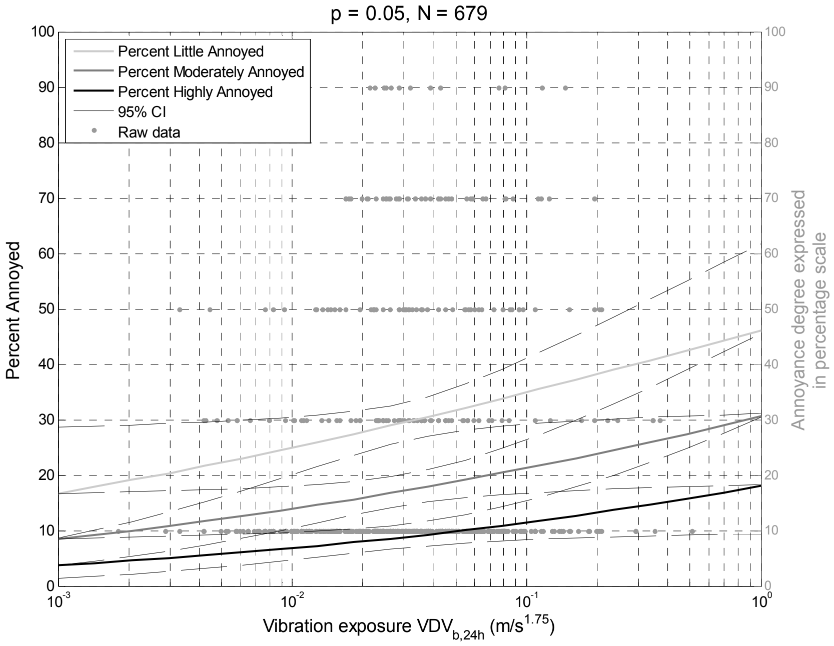

Figure 51. Percent little (categories: “slightly”, “moderately”, ”very”, and “extremely”), moderately (categories: “moderately”, ”very”, and “extremely”), and highly annoyed (categories: ”very” and “extremely”) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via 5-point semantic scale.

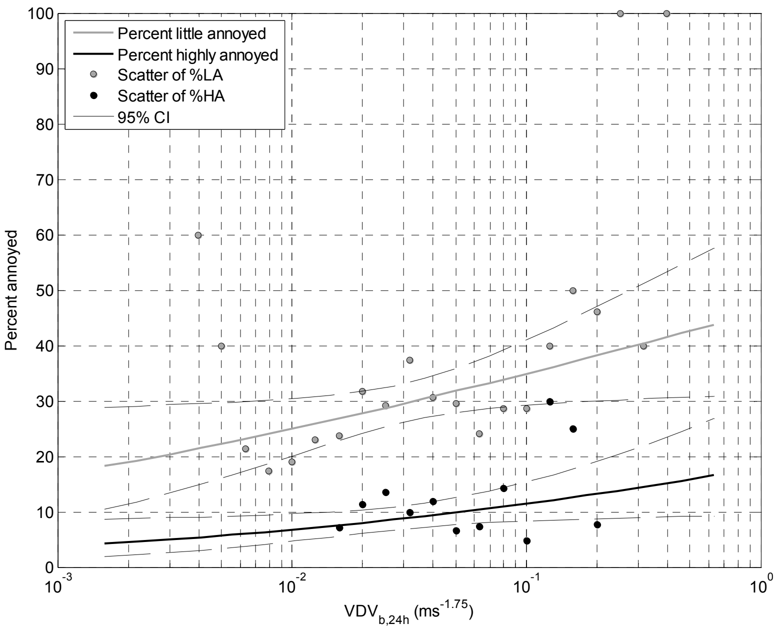

Figure 52. Percent little (categories: “slightly”, “moderately”, ”very”, and “extremely”), moderately (categories: “moderately”, ”very”, and “extremely”), and highly annoyed (categories: ”very” and “extremely”) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via 5-point semantic scale. The graphs also presents the scatter.

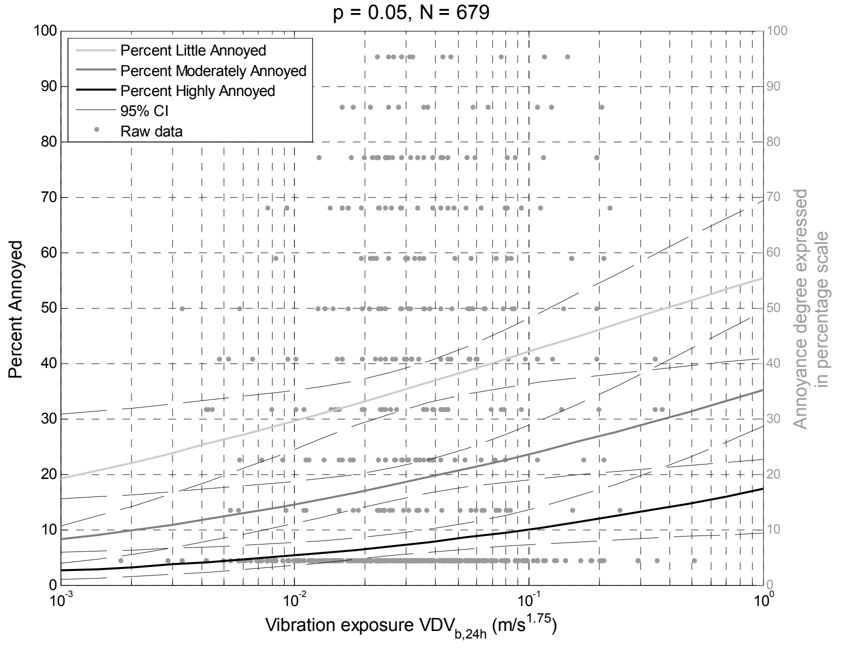

Figure 53. Percent little (categories from 4 to 11), moderately (categories from 6 to 11), and highly annoyed (categories from 8 to 11) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via 11-point numeric scale.

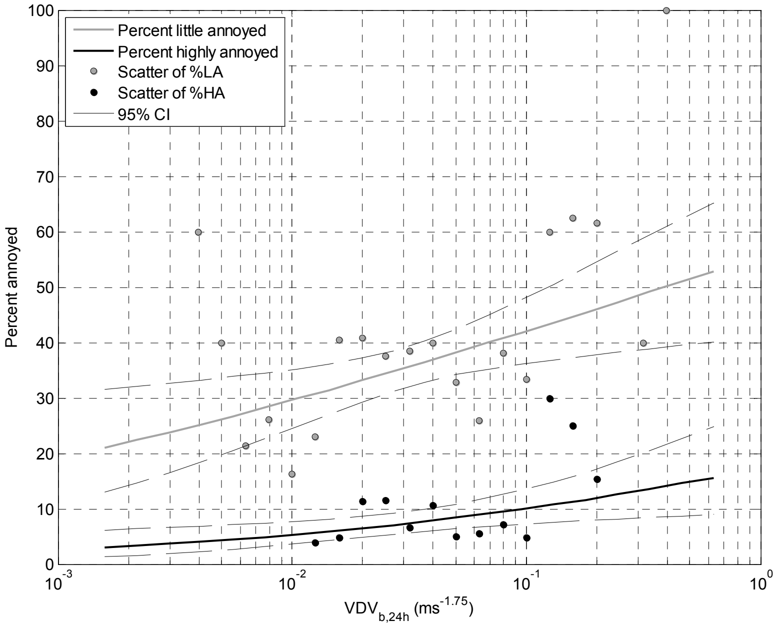

Figure 54. Percent little (categories from 4 to 11), moderately (categories from 6 to 11), and highly annoyed (categories from 8 to 11) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via 11-point numeric scale. The graphs also presents the scatter

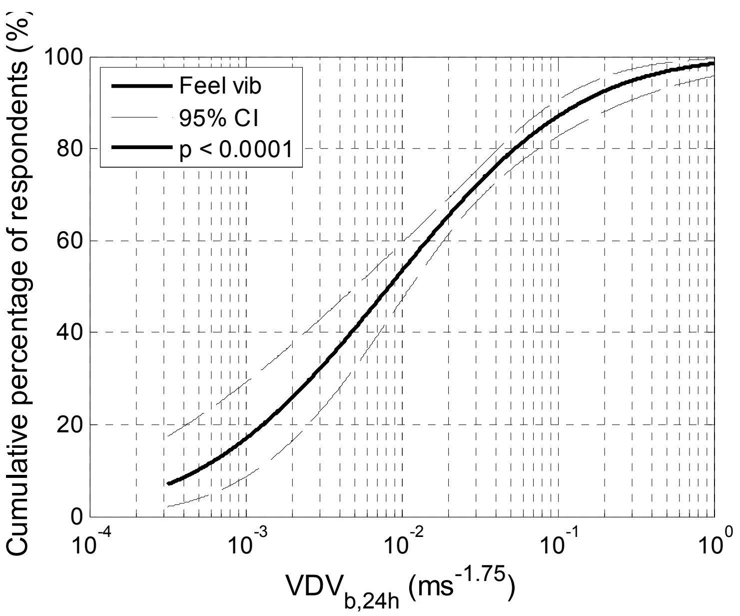

Figure 55. Percentage of respondents reported to feel vibration for a given exposure in VDV$_{b,24h}$(ms$^{-1.75}$) % of confidence intervals. Units are VDV$_{b,24h}$(ms$^{-1.75}$).

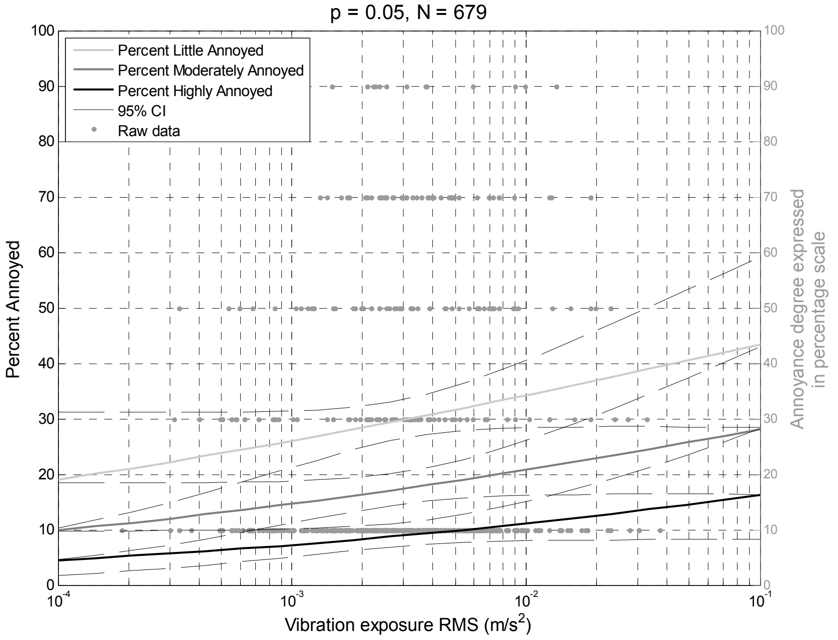

Figure 56. Percent little (categories: “slightly”, “moderately”, ”very”, and “extremely”), moderately (categories: “moderately”, ”very”, and “extremely”), and highly annoyed (categories: ”very” and “extremely”) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via 5-point semantic scale.

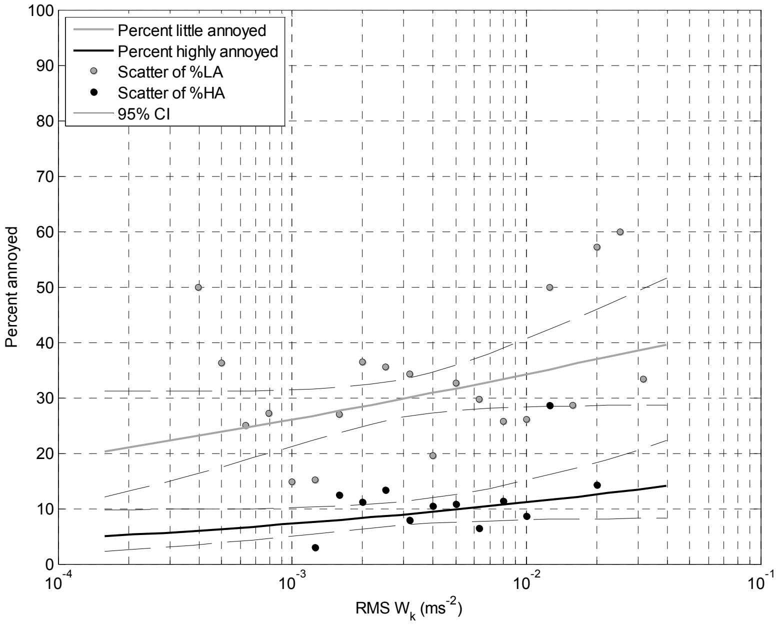

Figure 57. Percent little (categories: “slightly”, “moderately”, ”very”, and “extremely”), moderately (categories: “moderately”, ”very”, and “extremely”), and highly annoyed (categories: ”very” and “extremely”) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via 5-point semantic scale. The graph also presents the scatter.

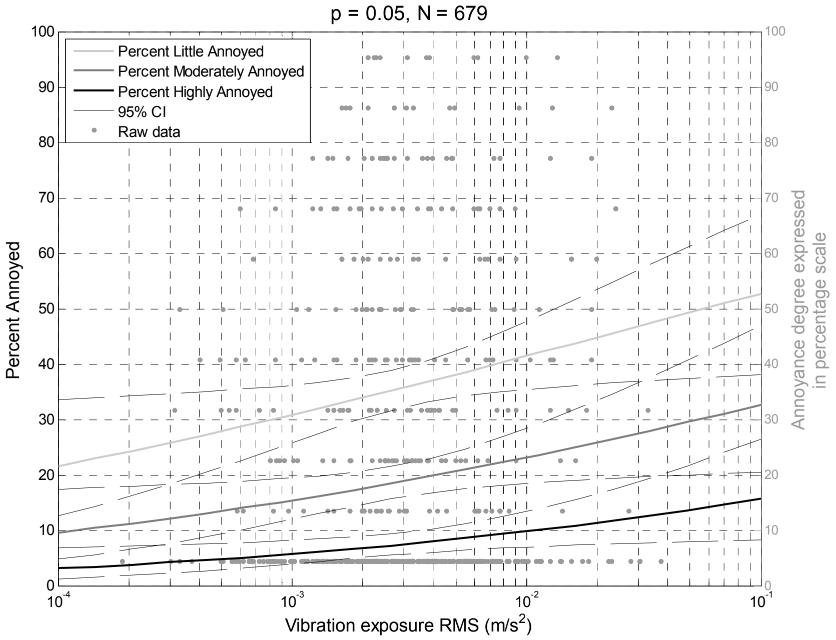

Figure 58. Percent little (categories from 4 to 11), moderately (categories from 6 to 11), and highly annoyed (categories from 8 to 11) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via11-point numeric scale.

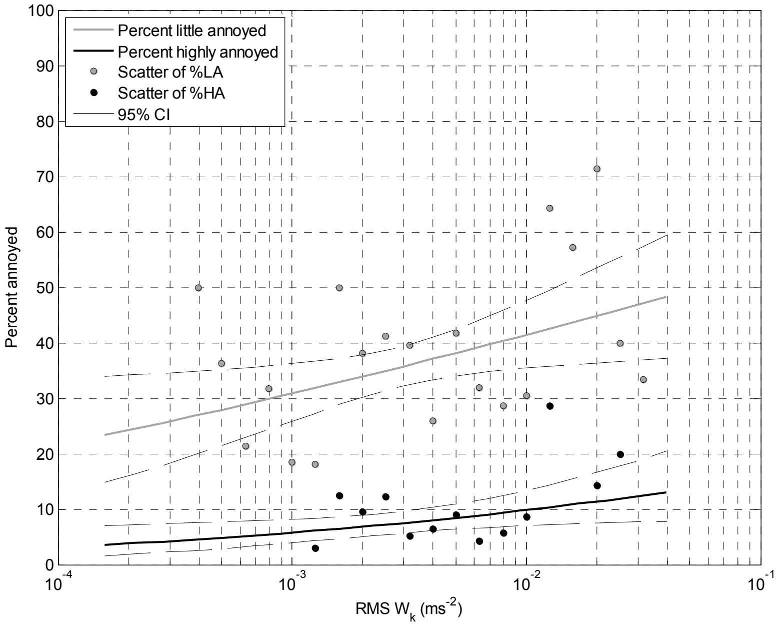

Figure 59. Percent little (categories from 4 to 11), moderately (categories from 6 to 11), and highly annoyed (categories from 8 to 11) vs. vibration exposure from railway with 95% Confidence Intervals. Annoyance measured via11-point numeric scale.

5.5.2. Sleep disturbance occurrences due to vibration exposure

Sleep disturbance is found to have an effect on annoyance when noise exposure is considered. More people report little, moderate, or high annoyance when subset of those reporting sleep disturbance is taken into account (See Figure 41). The same effect has been found while vibration exposure occurs (See Figure 60 (Woodcock, Peris, et al., 2011)).

The proportion of those who report disturbance at night is growing from 5% (2% - 12%) to 55% (40-65%) for corresponding vibration exposure from 0.0009 $VDV_{b,24h}$ ($m/s^{1.75}$) to 0.5 $VDV_{b,24h}$ ($m/s^{1.75}$), respectively (See Figure 60 (Woodcock, Peris, et al., 2011)). For the same range of vibration exposure, proportion of highly annoyed increased from 3.7% (1.4% - 8.5%) up to 16% (9.2% - 25.5%). The numbers show that percentage of highly annoyed increased by about 10% whereas percentage of sleep disturbed increased by about 50%.

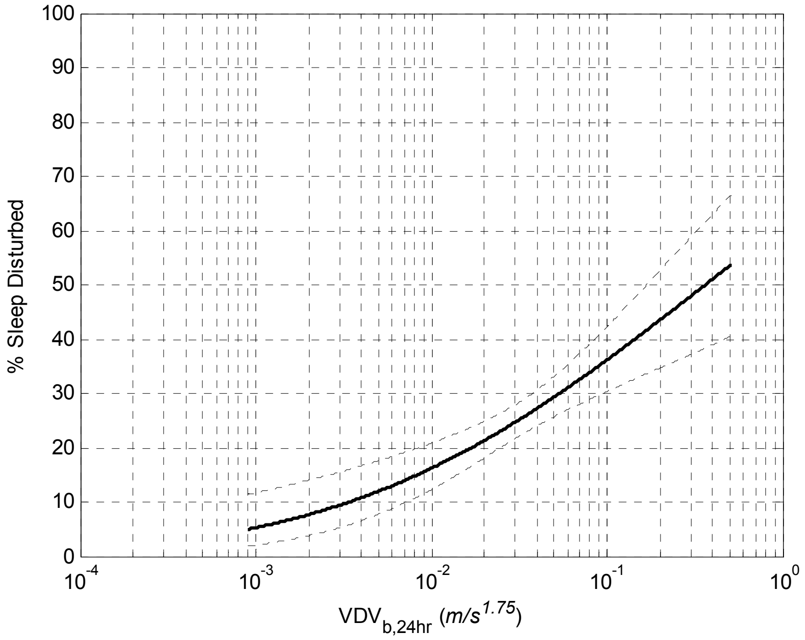

Figure 60. Exposure-response relationship showing the proportion of people reporting sleep disturbance for a given vibration exposure. (N = 755) (Woodcock 2011).

5.5.3. Conclusion

A number of people who report feeling vibration rapidly grows from about 10^{-3} VDV ($m/s^{1.75}$) to 10^{-1} $VDV_{b,24h}$ ($m/s^{1.85}$). It has been found that, regardless of a vibration metric or annoyance scales, the effect of vibration exposure on annoyance has the same tendency. The higher the vibration exposure, the higher is the percent annoyed considering each threshold (%LA, %MA, and %HA).

It is noteworthy that similar outcomes can be provided with regard to separate noise metrics related to day-time and night-time (Peris et al., 2012). During night-time period, probability of adverse comments is twice as much greater than during the day-time period (BS ISO 6472-1:2008, 2008) (See Table 26). However, it is not explained the meaning of the term "adverse comment". Peris et al. (2012) has investigated the percent highly annoyed at different time periods and concluded that the highest percentage of highly annoyed is found at night time, followed by evening time, and day time. It has concluded that, during night-time period, there is relatively larger percentage of people reporting high annoyance. This may be caused by issues related to the sleep disturbance or the fact that a greater number of freight trains operate at night.

Summarizing exposure-response relationship to vibration, an effect of vibration on annoyance is clear. Regardless of annoyance scale or applied vibration metrics, the higher vibration exposure, the greater is percentage of annoyed (%LA, %MA, and %HA).

5.6. COMBINED EFFECTS FROM NOISE AND VIBRATION

By this point, the discussion has been concentrated on noise and vibration as if those exposures occur separately. The great effort has been put on analyses of combination of these two phenomena with regard to annoyance. Therefore, in this section, results from analysis of combined effects from noise and vibration are presented. As with noise and vibration, analyses are conducted with respect to two annoyance scales, both vibration indices $VDV_{b,24h}$ and RMS W_k, and noise index L_{den}.

The graph included in Figure 61 illustrates exposure-response relationship to combined exposures. Analysis of this relationship has revealed that interaction between noise and vibration is not statistically significant. On the other hand, the independent contribution of the individual effects was found significant: noise with $p < 0.0001$, whereas vibration with $p < 0.05$. This outcome is different from findings by Öhrström (1997). According to this paper, interaction is expected to be significant.

Seven other figures followed by Figure 61 (from Figure 62 to Figure 68) illustrate variations in proportion of annoyed. The graphs vary because of application of different annoyance scales and vibration metrics combined with L_{den}. The full combination regarding relationship between noise, two vibration metrics, and two annoyance scales are included in the section before summary (5.7). Three-dimensional graphs also illustrate proportion of annoyed but represented by the surfaces. These graphs confirm an additive effect between noise and vibration with respect to annoyance. The situation when vibration is held at its mean is presented in Figure 61 and Figure 65. On the other hand, Figure 62 and Figure 66 illustrated wider confidence intervals due to uncertainty evaluated for noise exposure that have been included in the estimation. The vibration is held at following values: $VDV_{b,24h\ (mean)} = 0.045\ ms^{-1.75}$ and RMS $W_{k\ (mean)} = 0.00417\ ms^{-2}$.

Confidence intervals have been estimated utilizing two approaches. The narrower CIs are only the effect of estimation of a regression model. On the other hand, the wider CIs include both estimated CIs from the regression model and the errors estimated from prediction of noise. From analysis of errors and uncertainties considering all assumptions, it has been found that maximal error may reach ±10.0 dB(A).

The error value estimated from measurements of noise was found to be much lower and equal to ±2 dB(A). However, due to technical constraints, it was impossible to obtain all data from measurements.

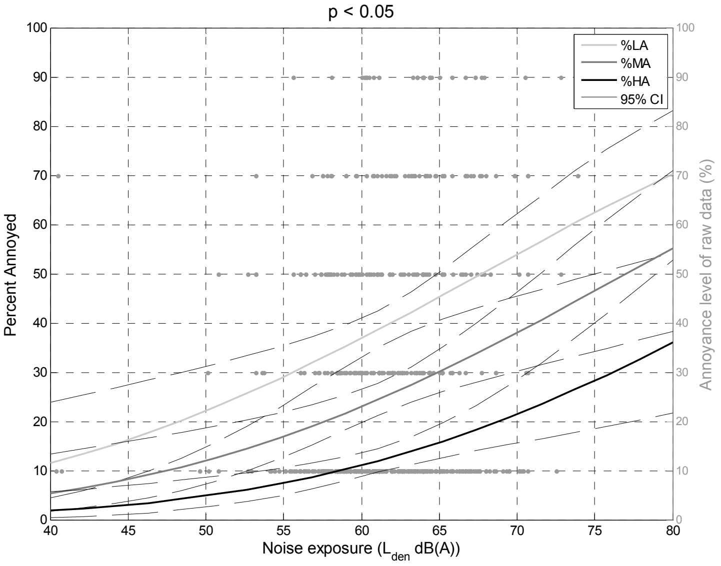

Figure 61. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant $VDV_{b,24h} = 0.045\ ms^{-1.75}$. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale.

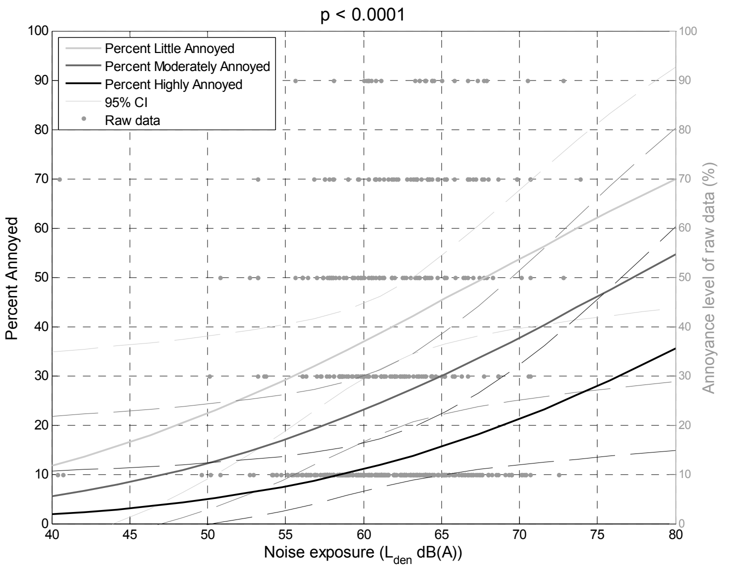

Figure 62. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant $VDV_{b,24h} = 0.045$ $ms^{-1.75}$. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale. Included error in CI from prediction.

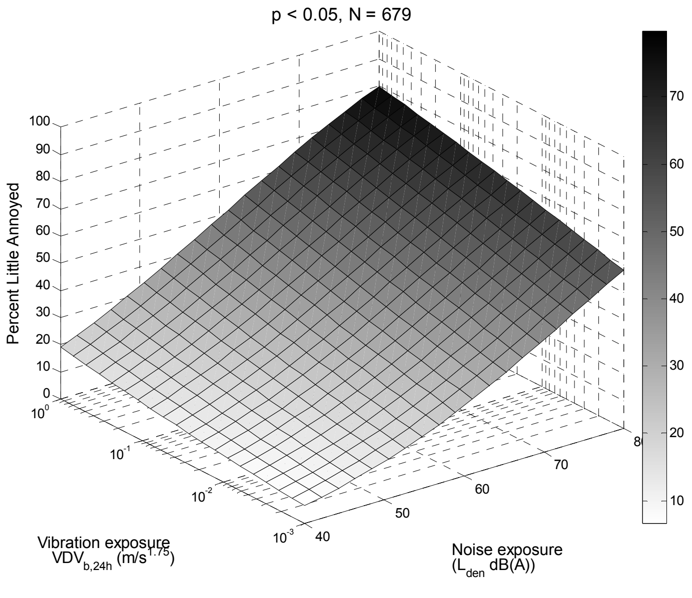

Figure 63. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent little annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

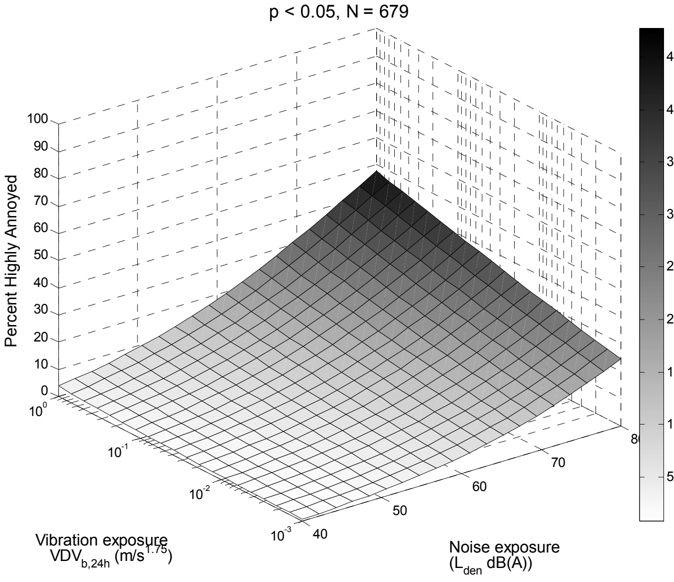

Figure 64. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent highly annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

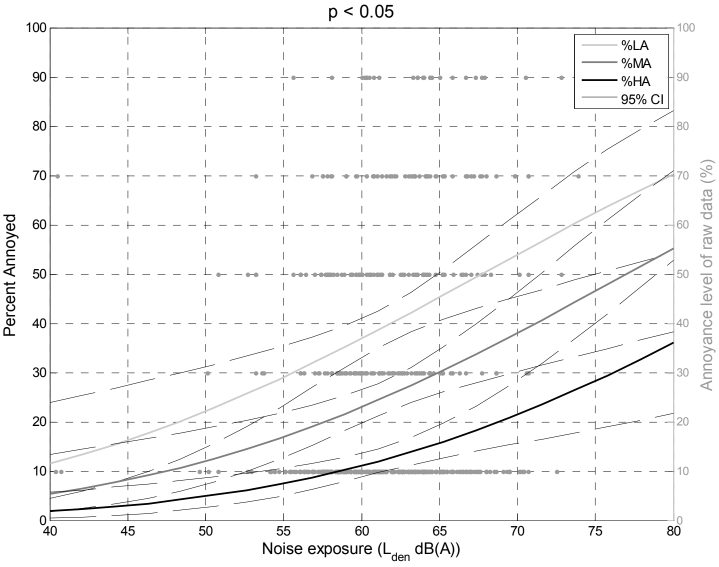

Figure 65. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant RMS W_k = 0.00417 ms^{-2}. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale.

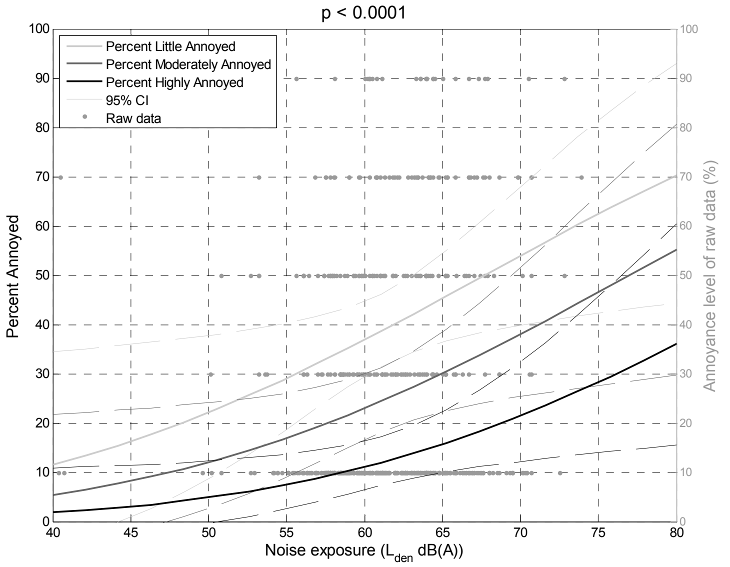

Figure 66. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant RMS W_k = 0.00417 ms^{-2}. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale. Included error in CI from prediction.

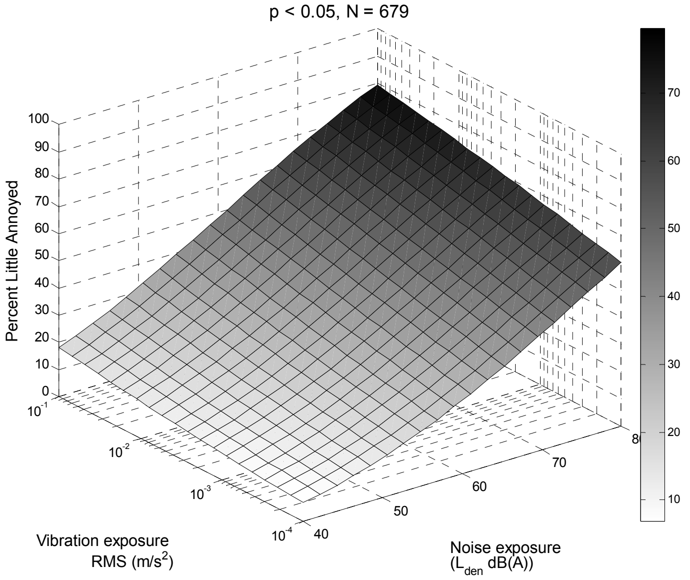

Figure 67. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent little annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

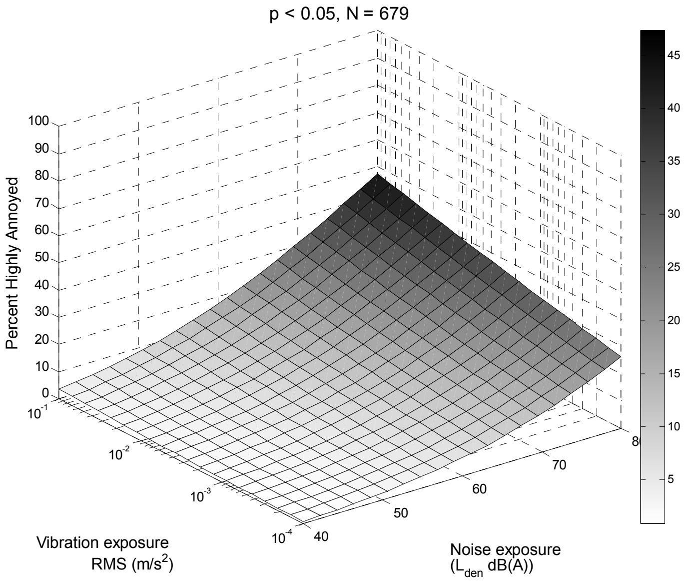

Figure 68. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent highly annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

5.6.1. Discussion

Comparison of figures representing exposure-response relationship to noise with figures representing exposure-response relationship to noise and vibration shows little or no changes when variation is included (for instance Figure 27 and Figure 61). However, included vibration illustrated by Figure 61 is held at $VDV_{b,24h}$ equal to 0.045 m/s$^{1.75}$. The additional variations are revealed in three-dimensional graphs.

The meaning of such outcomes is not known. However, lack of the interaction in the regression model might cause that kind of result. The other hypothesis could be related to the fact that participants are simultaneously exposed to combination of exposures regardless of a number of considered effects. In fact, participants are exposed to many other effects some of which could be dust or odour (Botteldooren et al., 2004; Winneke et al., 1996). This could give the conclusion that analysis of only one separate exposure inevitably assumes the effect of the second exposure. By introducing the third variable and analyse variation around its range, the effect can be fully investigated. If Figure 65 and Figure 27 show similar shapes, then it can be assumed that the vibration exposure could already occur and influence on reported annoyance, even though it was has not been considered in analyses of noise exposure.

Consequently, the three-dimensional graphs have been included to provide an opportunity to analyse this issue. Figure 64 and Figure 68 show the surfaces representing thresholds determining proportion of people reporting high annoyance. The gradients change slowly at lower levels of noise and vibration and rapidly increase when one of the variables reach one of the highest levels. The gradients are almost zero at very low levels of exposures implying that the proportion of reporting high annoyance is almost zero as well.

It is reasonable outcome because outdoor noise can hardly be heard at level of noise exposure slightly over 45 dB(A). There is always existing indoor background noise easily exceeding the level of outdoor noise. In terms of vibration, Table 26 and Table 27 indicate proportion of residents complaining about vibration. The lowest threshold is 0.1 of $VDV_{b,day}$ and $VDV_{b,night}$ whereas the highest considered level is equal to 1.6 of $VDV_{b,day}$ and $VDV_{b,night}$ Figure 52 shows the range in $VDV_{b,24h}$ of vibration obtained from measurements and confirms that this range is between 0.0018 $VDV_{b,24h}$ ($m/s^{1.75}$) and 0.509 $VDV_{b,24h}$ ($m/s^{1.75}$). The measured maximal VDV value of vibration falls into the thresholds of "*Adverse comments possible*" for day-time period and "*Adverse comments probable*" during night-time period, although the table contains separate indices with regard to day and night time periods. According to Table 26 and Table 27, less than 3% during the day time and less than 12% during the night time of proportion of highly annoyed is expected to report this annoyance degree.

On the other hand, at highest levels of noise exposures over 70 dB(A) the source is can be inevitably noticeable while occurring outside property. Therefore, annoyance increases rapidly at these levels. Also regarding vibration, Table 26 and Table 27 suggest that more than 15% or even 19% of people reporting high annoyance are expected to report this annoyance degree. Figure 64 suggests over 40% of people would report high annoyance. As said, it is an additive characteristic but these effects cannot sum arithmetically. The same person may report high annoyance regardless of noise or vibration and that person cannot be counted twice.

It has been not investigated whether a magnitude of noise exposure has a strong or weak effect on the judgment of annoyance caused by vibration or vice versa. It may require laboratory study in control environment to investigate this issue. For instance, a similar to this problem studied were already conducted (Howart et al., 1990; Howarth, 1991; Howarth et al., 1990; Paulsen et al., 1995).

It is also worth considering that according to Figure 69 (Woodcock, Peris, et al., 2011) vibration from railway traffic was below the threshold of felling vibration. It has been commented by Woodcock, Peris, et al. (2011) that the threshold curve from (BS 6472:1992) was obtained in controlled environment. This demonstrates a different result comparing to Figure 55 which clearly shows that at certain vibration exposure there are more than 50% respondents who could feel vibration; this even reaches the value of ~ 97% at very high exposures. Woodcock, Peris, et al. (2011) argues that "when considering frequency weightings, it is important to ensure that respondents were exposed to excitations with a range of different frequency content. [Figure 69] shows [a boxplot] of distribution of RMS acceleration in each 1/3 octave band for 751 estimates of internal vibration exposure in the vertical (...) [direction] respectively. It can be seen from [the figure] that each 1/3 octave band exhibits a wide dynamic range of exposures. These magnitudes are also compared to the perception threshold base curves presented in previous versions of BS 6472-1. It can be seen that these exposures are generally at or below the thresholds indicated by the base curves. However, as was highlighted in previous sections, the perception threshold base curves are derived from laboratory studies and therefore may not be directly applicable to vibration perception in residential environments" (Woodcock, Peris, et al., 2011, p. 27).

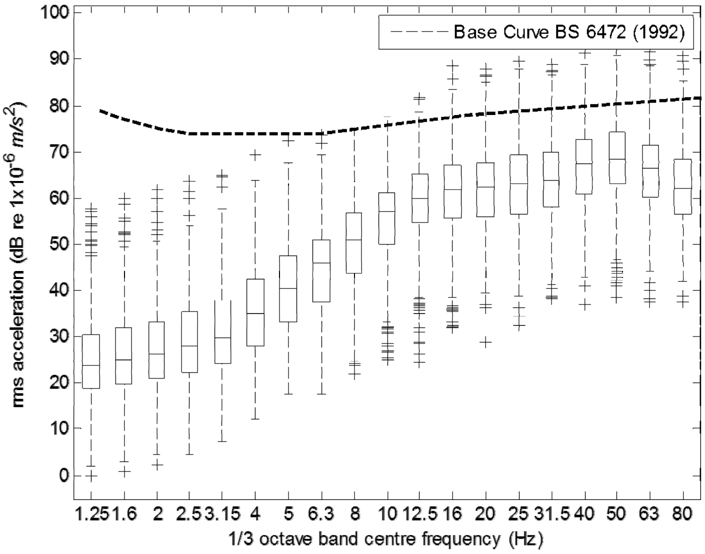

Figure 69. Boxplot illustrating the distribution of *rms* acceleration in 1/3 octave bands in the vertical direction for 751 estimations of internal vibration exposure. Also shown is the vibration perception base curve from (the now superseded) BS 6472-1:1992.

5.7. ADDITIONAL FIGURES PRESENTING ANNOYANCE DUE TO COMBINED EFFECTS FROM NOISE AND VIBRATION EXPOSURE

This section provides all combination of noise, vibration metrics, and annoyance scales. It was though that presenting following graphs would help with improvement of understanding the phenomena that is response to combined exposures from nose and vibration. The following graphs can be found in next subsections:

- Annoyance (measured via 5-point semantic scale) level versus noise combined with vibration expressed by VDV
- Annoyance (measured via 5-point semantic scale) level versus noise combined with vibration expressed by RMS
- Annoyance (measured via 11-point numeric scale) level versus noise combined with vibration expressed by VDV, and
- Annoyance (measured via 11-point numeric scale) level versus noise combined with vibration expressed by RMS.

In all subsections, three-dimensional graphs of each instance are also included.

5.7.1. Noise exposure combined with vibration expressed by $VDV_{b,24h}$ ($ms^{-1.75}$) and related to 5-point semantic annoyance scale.

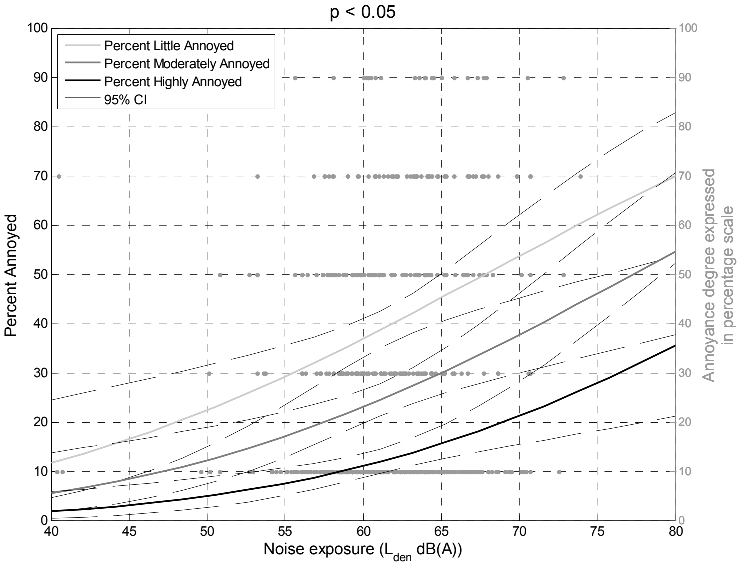

Figure 70. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant $VDV_{b,24h} = 0.045\ ms^{-1.75}$. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale.

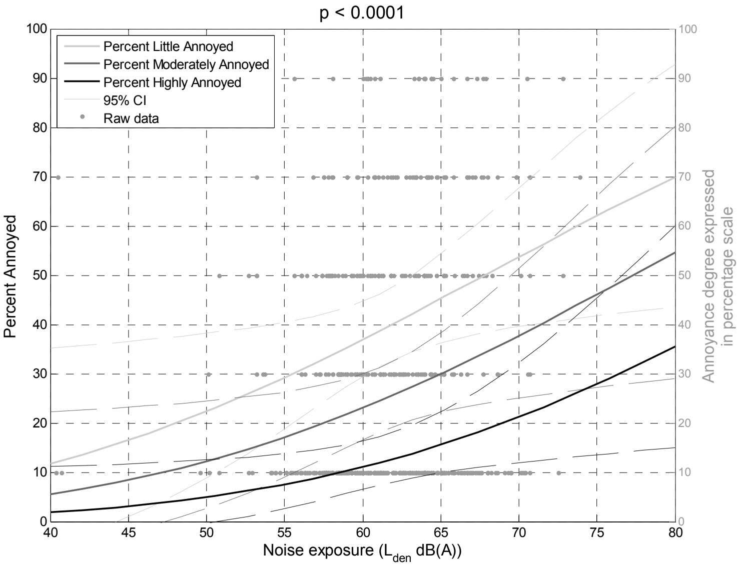

Figure 71. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant $VDV_{b,24h} = 0.045\ ms^{-1.75}$. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale. Included error in CI from prediction.

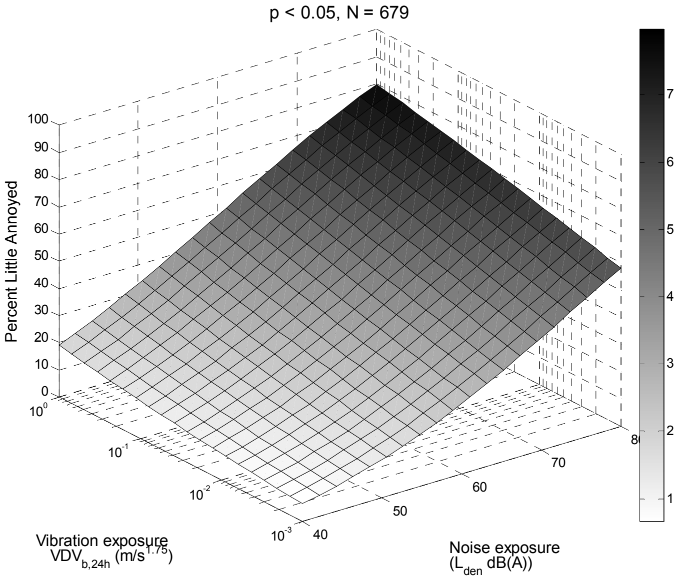

Figure 72. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent little annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

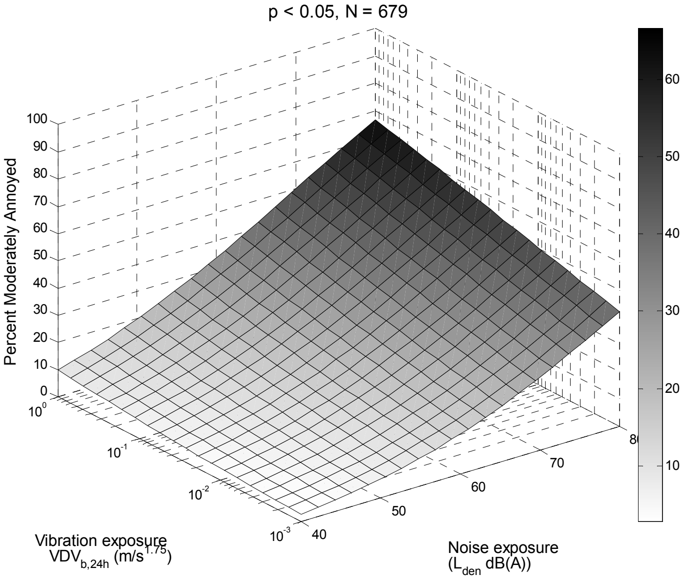

Figure 73. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent moderately annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

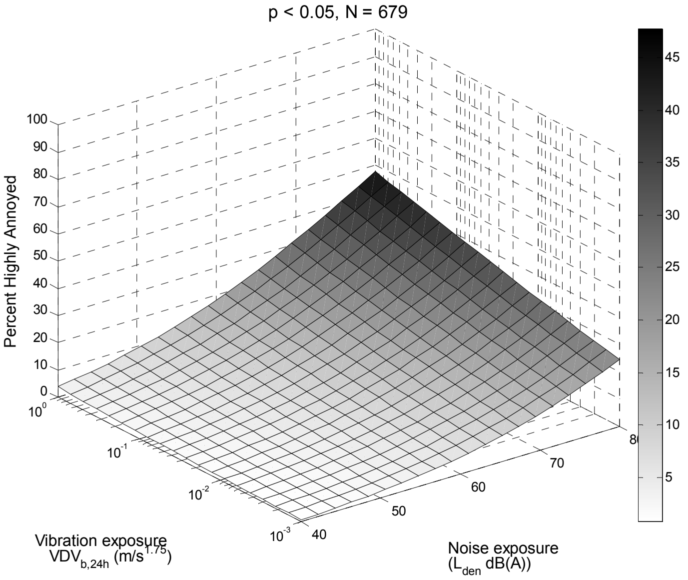

Figure 74. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent highly annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

5.7.2. Noise exposure combined with vibration expressed by RMS W_k (ms^{-2}) and related to 5-point semantic annoyance scale.

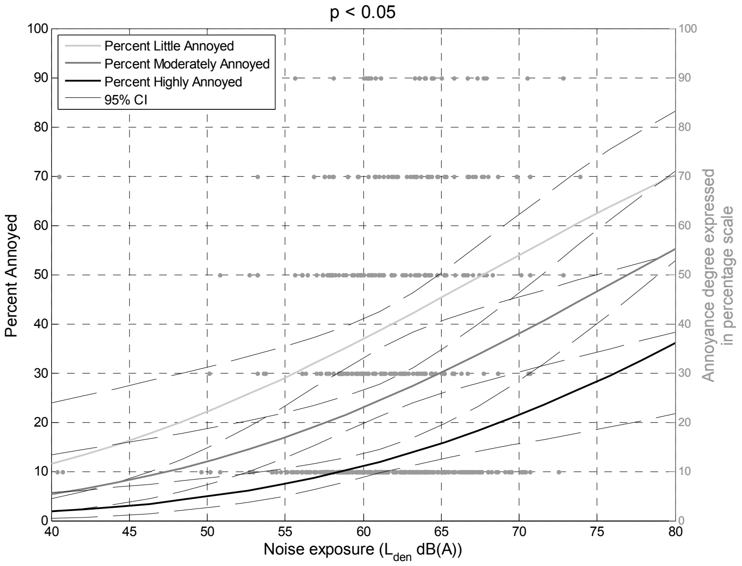

Figure 75. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant RMS $W_k = 0.00417$ ms^{-2}. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale.

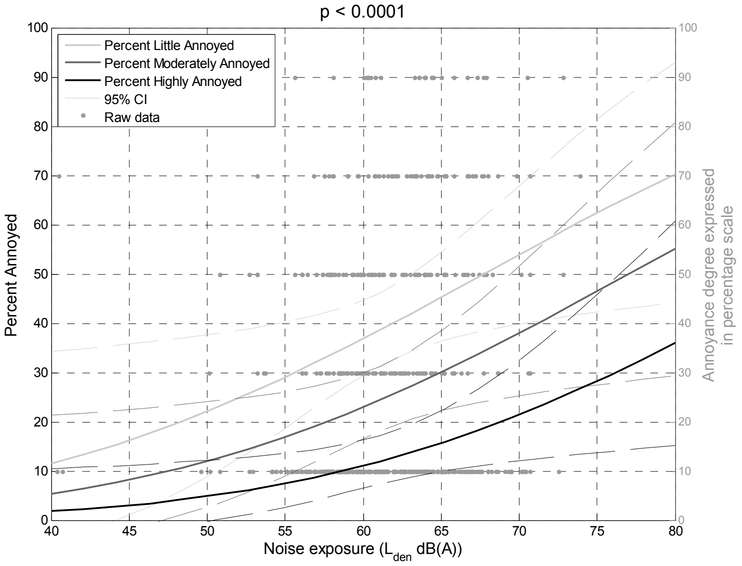

Figure 76. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant RMS $W_k = 0.00417$ ms^{-2}. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 5-point semantic scale. Included error in CI from prediction.

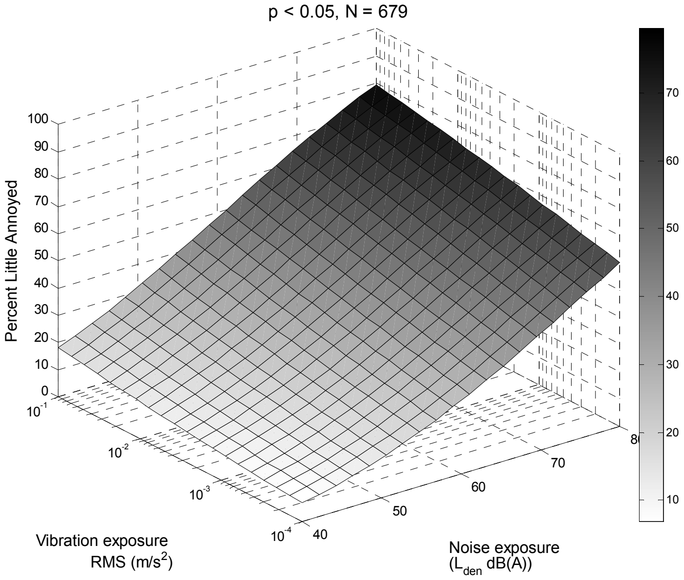

Figure 77. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent little annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

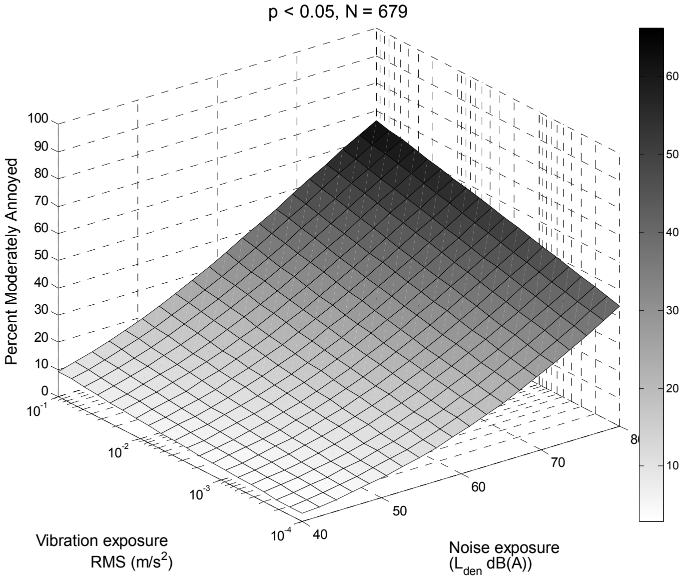

Figure 78. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent moderately annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

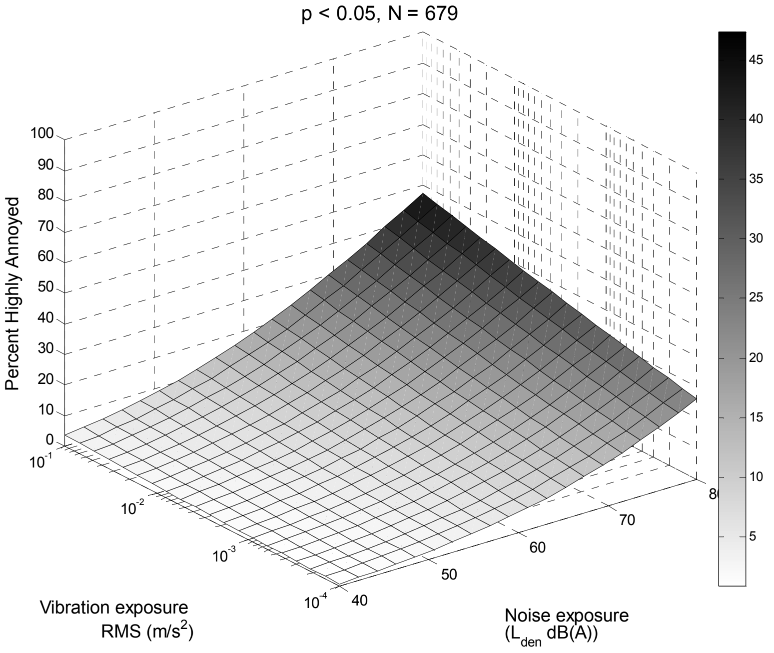

Figure 79. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent highly annoyed** in 5-point semantic scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

5.7.3. Noise exposure combined with vibration expressed by $VDV_{b,24h}$ (ms$^{-1.75}$) and related to 11-point numeric annoyance scale.

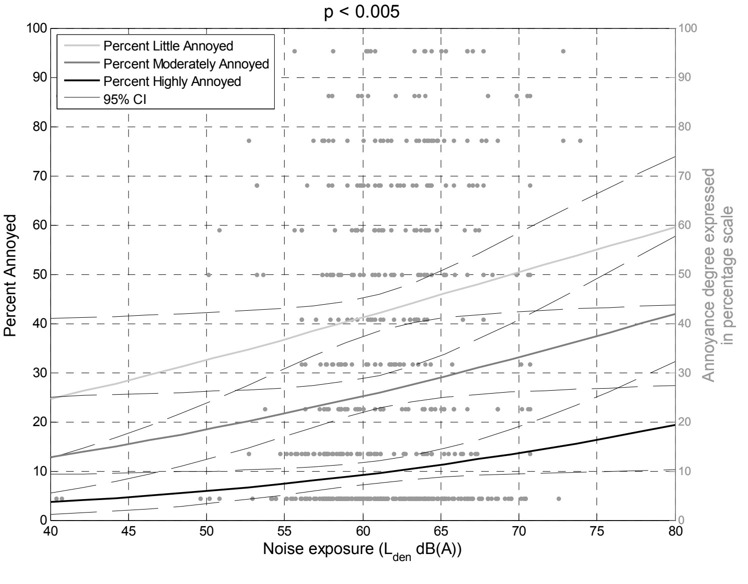

Figure 80. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant $VDV_{b,24h}$ = 0.045 ms$^{-1.75}$. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 11-point numeric scale.

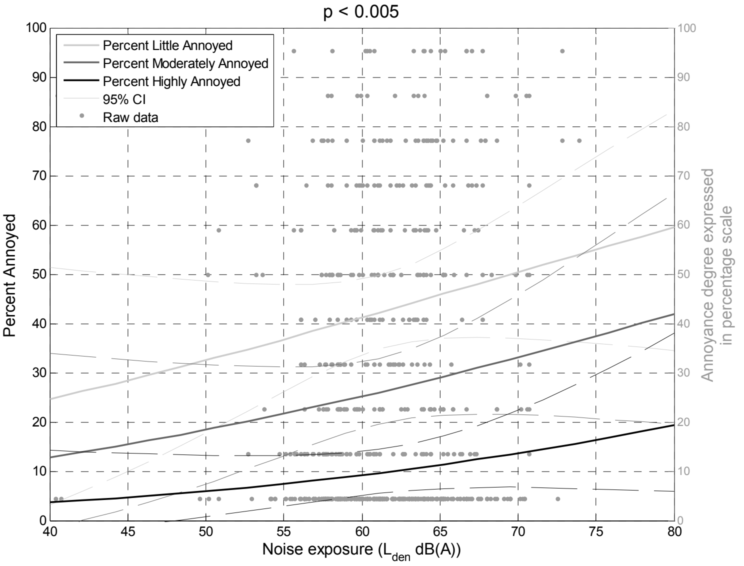

Figure 81. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant $VDV_{b,24h} = 0.045$ $ms^{-1.75}$. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 11-point numeric scale. Included error in CI from prediction.

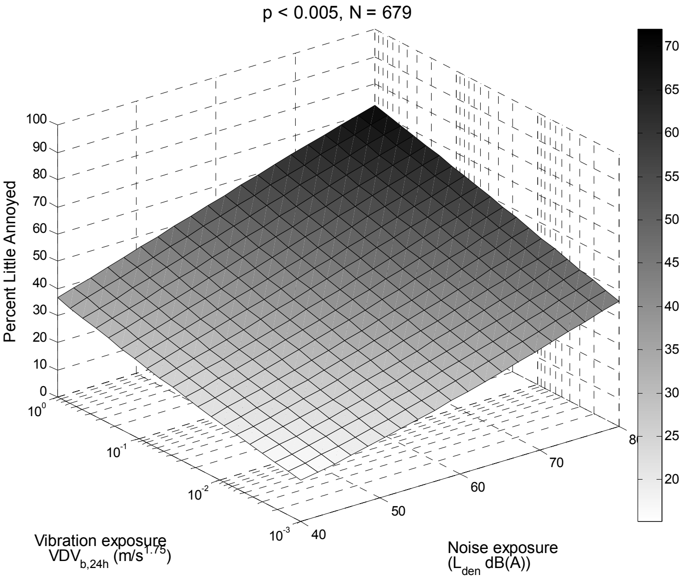

Figure 82. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent little annoyed** in 11-point numeric scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

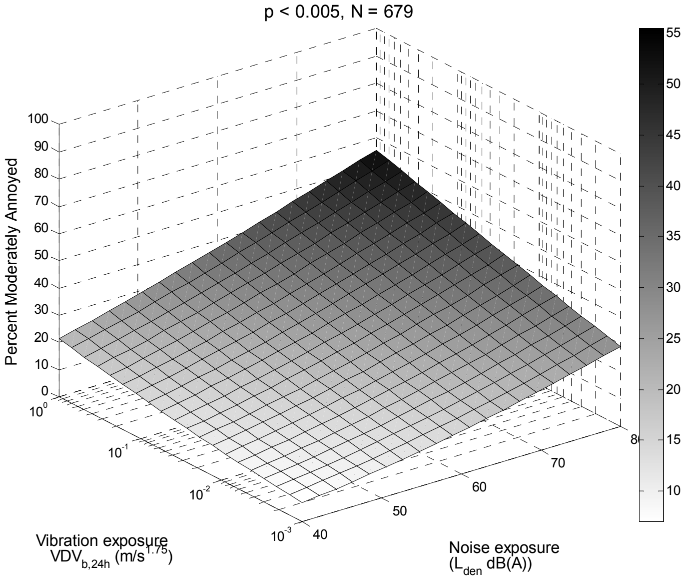

Figure 83. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent moderately annoyed** in 11-point numeric scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

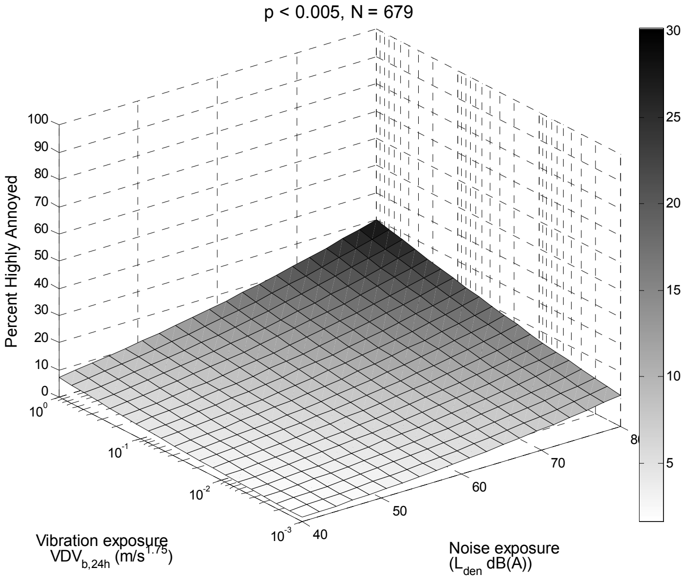

Figure 84. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent highly annoyed** in 11-point numeric scale. Noise (L_{den} /dB(A)) is combined with vibration ($VDV_{b,24h}$ /$ms^{-1.75}$).

5.7.4. Noise exposure combined with vibration expressed by RMS W_k (ms^{-2}) and related to 11-point numeric annoyance scale.

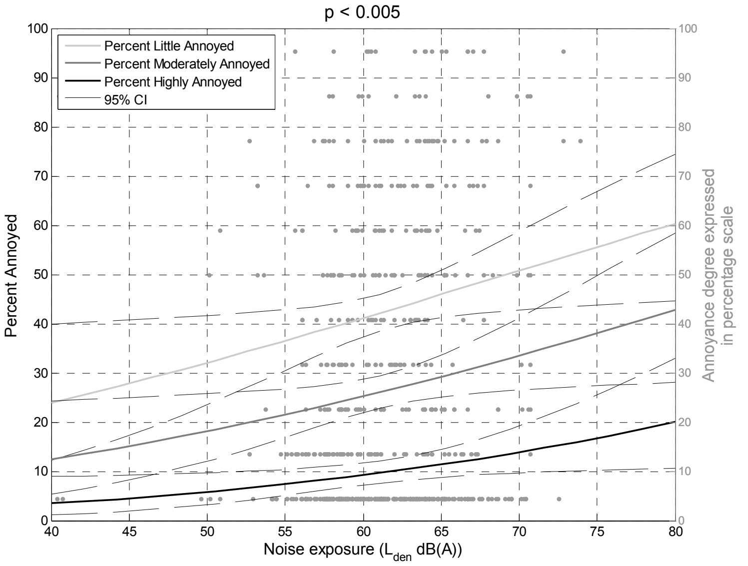

Figure 85. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant RMS W_k = 0.00417 ms^{-2}. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 11-point numeric scale.

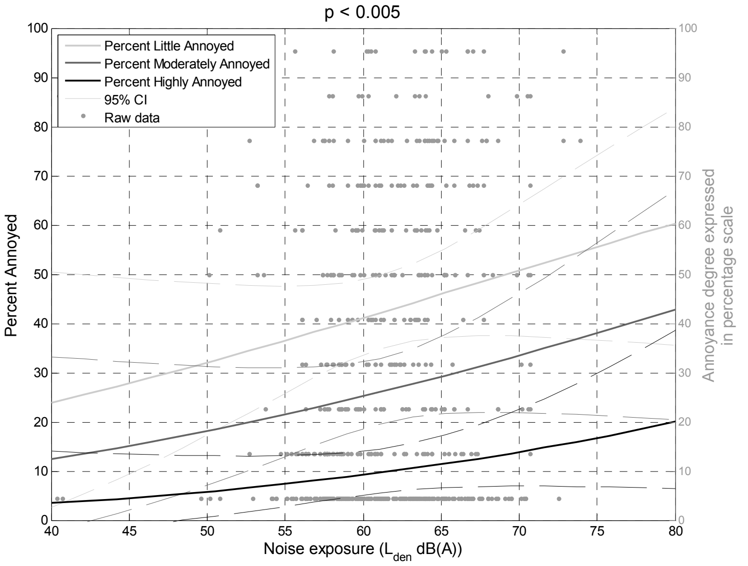

Figure 86. Cumulative distribution functions of annoyance against noise. L_{den} is combined with vibration held at the constant RMS W_k = 0.00417 ms^{-2}. Cut-off curves represent thresholds that determine proportion of people exceeding reported annoyance degrees: percent little annoyed (%LA), percent moderately annoyed (%MA), and percent highly annoyed (%HA). Annoyance is expressed in 11-point numeric scale. Included error in CI from prediction.

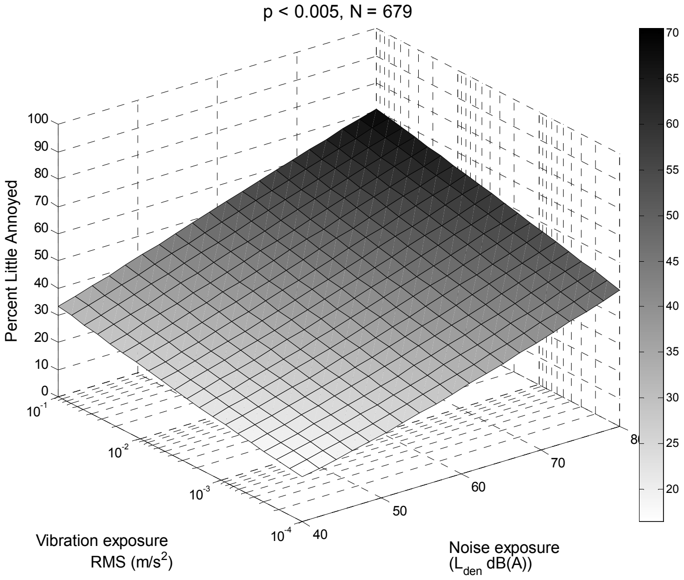

Figure 87. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent little annoyed** in 11-point numeric scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

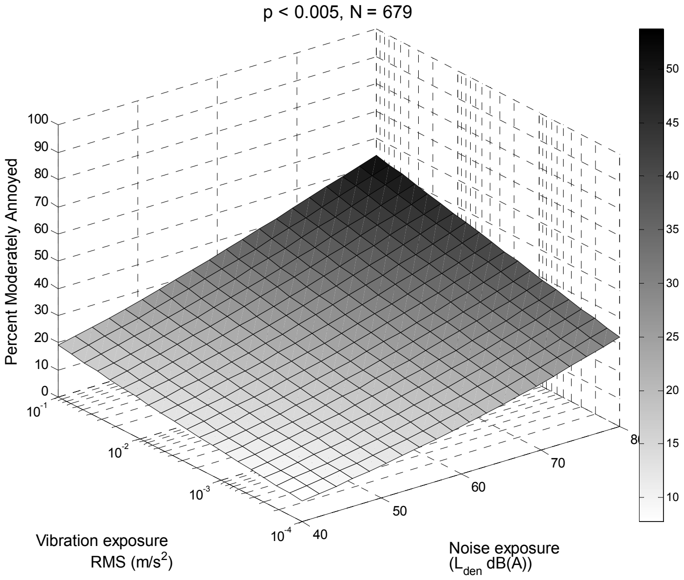

Figure 88. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent moderately annoyed** in 11-point numeric scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

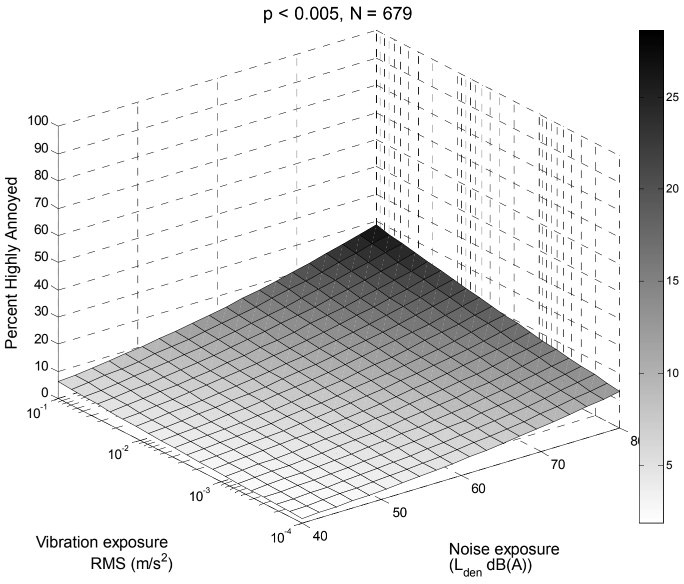

Figure 89. Cumulative distribution of annoyance. The surface represents a threshold that determines **percent highly annoyed** in 11-point numeric scale. Noise (L_{den} /dB(A)) is combined with vibration (RMS W_k /ms^{-2}).

5.8. SUMMARY

This chapter discussed results from analysis of noise, vibration, and combination of these two. In terms of noise and vibration, proportion of annoyed was found increasing when either effect was higher. While both effects occurred, proportion of annoyed changed whenever each of the effects varied.

Noise exposure was further investigated with regard to sleep disturbance. It was found that proportion of highly annoyed who reported sleep disturbance was greatly increased. Therefore, it could be concluded that sleep disturbance have a strong if not the strongest effect on annoyance from transportation noise. The same outcome was found when sleep disturbance was investigated with respect to vibration exposure. From all the set of participants, a larger proportion of annoyed could be observed when vibration exposure increased. In conclusion, sleep disturbance has an effect on annoyance and was found to be highly influential regardless of each exposure.

Along with sleep disturbance, other factors such as gender, age, noise sensitivity, and noise acceptance were investigated with regard to noise exposure. Age was found to have an effect on annoyance from railway traffic noise. There was no evidence that gender had any effect on annoyance. The outcome was confirmed from the reviewed literature and by conducting non-parametric statistic test and. The results confirm that noise acceptance has an effect on annoyance but this effect is rather mediocre.

Noise acceptance, on the other hand, was found the least contributing factor to annoyance. It was confirmed from distribution of responses that the majority of participants reported category “Not at all” (~52%). This is followed by reported category “Slightly” (~23%). These two categories sum to a little over 75% of all responses. Exposure-response relationship was drawn in such the way that the relationship was controlled for noise sensitivity. There is little evidence that exposure-response relationship increase when higher category of noise sensitivity is considered but the changes are small and may be non-significant.

Exposure response-relationship was presented via couple of figures. It can be observed that proportion of annoyed increases when vibration exposure is higher. When this effect is considered at different time periods, the largest proportion of highly annoyed is reported at night. This is somehow in accordance with (BS ISO 6472-1:2008, 2008). This standard suggests that “adverse comments” are *probable* and *possible* when vibration exposures are twice as much lower at night-time than at daytime periods. The same trend is confirmed by (Woodcock, Waddington, et al., 2011). Vibration exposures were expressed by two indices such as $VDV_{b,24h}$ and RMS W_k. The choice was dictated by ease of calculation, interpretability, current practice, and the measurement capability of the user of the exposure-response relationship. Vibration is also analysed with respect to sleep disturbance. It could be concluded that number of disturbed during night-time increased while vibration exposure increases.

The chapter ended with discussing combined effects from noise and vibration. The main conclusion from the last section refer to increases of vibration or noise exposure that cause increases of proportion of little, moderately, and highly annoyed, as well. This could be confirmed by inspecting three-dimensional graphs also presented in the last section.

6. CONCLUSION

The main objective of this project was to investigate individual exposure-response relationships to noise and vibration as well as exposure-response relationship to combined effects. According to the literature, a number of non-acoustical factors contributing to annoyance exists. From this point of view, it was hypothesised that factors such as gender, noise sensitivity, noise acceptance, distance, age, and sleep disturbance may or may not have a strong effect on annoyance. In existing database, noise, combination of noise and vibration, sleep disturbance, noise sensitivity, and noise acceptance were assessed via 11-point numeric and 5-point semantic scales with regard to response to noise. When vibration as a single exposure was investigated then 5-point semantic and 11-point numeric scales with regard to vibration response were used.

The definition of percent little, moderately, and highly annoyed can be found elsewhere (See section 3.2).

For this project, Noise exposure was calculated using Calculation of Railway Noise for 931 cases. Vibration exposure was measured (Peris et al., 2011) and calculated (Sica et al., 2011) to obtain vibration exposure expressed by two indices $VDV_{b,24h}$ and RMS W_k. The description of the choice of these two indices can be found in chapter 4 (See section 4.3).

Noise exposure was analysed as a single effect on annoyance. The literature reviewed shows that annoyance increase when noise exposure increase as well as the proportion of people is expected to increase when noise exposure increases. It can be confirmed from the results of this work that noise exposure influences negatively on a quality of life causing residents to be disturbed especially at night time period. Annoyance was measured via two response scales and results are presented with respect to both scales.

It was expected that proportion of people reporting to be annoyed would be higher when noise exposure increases. This was assessed via both 5-point semantic and 11-

point numeric scales. When 5-point semantic scales is considered, about 5% of respondents reported to be highly annoyed at the level of 50 dB(A) of L_{den}, followed 12% reported to be moderately annoyed, and 22% reported to be little annoyed. When 11-point numeric scales is considered, about 5% of respondents reported to be highly annoyed at the level of 50 dB(A) of L_{den}, followed 18% reported to be moderately annoyed, and 32% reported to be little annoyed. The number of respondents increases when noise exposure increases as well. For instance, considering 5-point semantic scale, the number of reporting high annoyance increased by 10% when level noise exposure increased by 20 dB(A). A number of people reporting little annoyance has increased by 33% given the same level of noise exposure.

According to Miedema's paper (Miedema et al., 2001), from railway traffic noise, about 1.1% of people would report to be highly annoyed at level of 50 dB(A) of L_{den}, followed by 5% to be moderately annoyed, and 16.2% to be highly annoyed. These would increase by 13.8%, 29.7%, and 44.2% with regard to highly, moderately, and little annoyed, respectively.

Percentages of people reporting to be annoyed are different from those found in the the paper by Miedema. Perhaps the main reason is that this case-study project is based on one study conducted for 931 cases around UK, when Miedema estimated the model based on thousands of cases found in different studies from different countries. Miedema has also estimated predictors including variation between studies, a component of the multiple grouped regression model.

The proportions of little, moderately, and highly annoyed were also found to be increasing while vibration exposure increases. The graphs from the section regarding vibration (See section 5.5) illustrate the changes in proportions of annoyed (from Figure 51 up to Figure 59). It can be observed that percentage of people who reported feeling vibration increases significantly from about 4% to almost about 98% at highest estimated vibration exposure. In conclusion, the greater number of people feeling vibration, the greater is proportion of little, moderately, and highly annoyed. The section regarding vibration also provides two tables (Table 26 and Table 27) in which vibration can be considered in two different time periods. These tables were produced elsewhere but provide important information on vibration occurrence during specified time periods.

By inspecting the Table 26, it can be seen that “adverse comments” can be either “probable” or “possible” (the same column of the table) from lower level of vibration exposure at night-time (BS ISO 6472-1:2008, 2008). Table 27 shows that percentage of people is significantly higher when considered proportion of people exposed to vibration at night. This is confirmed by (Peris et al., 2012) who provided a graph on which percentage highly annoyed from vibration is also significantly higher.

The vibration effect is also investigated with respect to sleep disturbance. As expected, a number of people who reported to be disturbed at night-time period is significantly higher when people are exposed to higher level of vibration. This may imply that sleep disturbance influence the judgment of annoyance caused by vibration, similarly to noise exposure.

The response was also investigated from two simultaneous effects: noise and vibration. Unfortunately, the combination was found to be simple and additive. The regression model was tested in terms of contribution of each component: noise + vibration + noise*vibration. It was found that the component responsible for the interaction was not found to be statistically significant. Therefore, this component was neglected in analyses of combined effects. Regardless of simple characteristic of these two effects, it was confirmed that vibration and noise contribute to each other resulting with increased proportion of annoyed.

An interesting point can be made about two graphs representing exposure-response relationship to noise (Figure 27) and exposure-response relationship to noise and vibration (Figure 61). By inspecting those two graphs, it can be seen that exposure-response relationships are almost identical. It is not possible to explain the meaning of this outcome from existing database. It would require additional experiments in controlled environments where levels of noise and vibration exposure would be carefully presented to subjects. Only then it would provide answers on each combination of levels of noise and vibration. Such experiments are already documented (Howart et al., 1990; Howarth, 1991; Howarth et al., 1990; Paulsen et al., 1995) and conclude that that noise has a strong effect on judgment of annoyance caused by vibration. Vibration, on the other hand, has not got a strong effect on judgment of noise caused by railway.

Another explanation for almost identical curves regarding exposure-response relationship to noise and combination of noise and vibration is presented in section results (See section 5.6.1). Concluding, analysis of only one separate exposure may inevitably assume the effect of the second exposure. By introducing the third variable and analyse variation around its range, the effect can be fully investigated. As such, the three-dimensional graphs have been provided that show the surfaces representing thresholds determining proportion of people reporting little, moderate, and high annoyance. The variation would probably reveal more aspects of this relationship if the interaction existed.

Another objective of this thesis was to investigate the influence on annoyance of non-acoustical variables such as gender, age, noise sensitivity, noise acceptance. The gender was simply not found contributing to annoyance. Age has a significant effect on annoyance. Confirmed from the literature (Gerven et al., 2009; Groothuis-Oudshoorn et al., 2006), the highest number of people reporting high annoyance is of age between 40-50. The article by Hilton et al. (2008) provides information on age and percentage of people who suffer from Age-Related Hearing Loss (ARHL). Prevalence of hearing loss in people of age over 50 years is estimated at 50% and in those older than 80 as being 90% (Huang, 2007). ARHL can be the explanation of a decreased number of highly annoyed of people of aged over 50. On the other hand, it is not known why a lower number of relatively younger people expressed to be highly annoyed whereas people of this age may not feel disturbance from railway traffic noise because they live in the environment that outdoor noise exposure is easily masked by indoor activities.

Noise sensitivity was assessed via 5-point semantic scale from social survey questionnaire. It was observed that majority of people expressed category “Not at all” indicating to be not sensitive to noise. There were about 52% of people who reported this category followed by 23% of those who reported “Slightly”. The other 25% of respondents answered such that only 10% of people reported to be “Very” and “Extremely” sensitive. According to definition of percent highly annoyed, percent highly sensitive can be those who reported two highest categories “Very” and “Extremely”. The exposure-response relationship controlled for noise sensitivity revealed that there is a little influence of noise sensitivity on annoyance caused by railway.

The last factor noise acceptance was investigated along with sleep disturbance. The analyses also include the test of association of sleep disturbance and noise acceptance. It could be concluded that sleep disturbance is negatively correlated with noise acceptance. When sleep disturbance increases, then it is expected that noise acceptance decreases and vice versa. The effect of noise acceptance was found strong on sleep disturbance controlled for noise exposure. The similar test was done regarding association of sleep disturbance for noise sensitivity. As with other outcome including this factor, noise sensitivity was one more time found to have very little effect on sleep disturbance.

In the line of conclusion, majority of research is in accordance with outcome from this work. There are couple of issues which could not be supported from the evidence of this work. However the overall work seems to support the findings from the literature along with contribution to the research.

7. FURTHER WORK

7.1. INTRODUCTION

This section provides information on further work that could improve the analysis conducted for this project or provide additional data to analyse. Noise index L_{den} is commonly used in analysis of exposure-response relationship to noise and annoyance. However, reviewed literature shows the other considerations especially with regard to transportation noise. Socio-acoustic studies assess a number of acoustical and non-acoustical variables. To overcome an overwhelming number of variables, principal component analysis or categorical principal component analysis could reduce the dimension of analysis. Consideration to measure ground-borne and structure-borne noise and vibration was also presented. It becomes especially important for people who live in vicinity to tunnels and who are exposed to this kind of phenomena. Vibration causes rattling in properties and induces a low frequency noise. It has been found in literature that at low very low frequency noise, people perceive a different form of experience.

7.2. APPLICATION OF NOISE INDICES FOR COMMUNITY RESPONSE TO RAILWAY TRAFFIC

Noise exposure was calculated according to a routine based on CRN (1995). CRN suggests and provides calculation of energy averaged noise index L_{den}. More noise indices would reveal a better description or association of noise exposure with annoyance (Langdon et al., 1982). However, that would involve measuring noise in situ. Statistic noise indices such as L_{A10} L_{A90}, and direct noise measure $L_{AF,max}$, $L_{Aeq,T}$ could help with more accurate descriptions of noise. It would also be useful if further research worked to find a way to associate noise with other factors such as number of events in terms of traffic of any kind, a number awakenings in terms of sleep disturbance, or tonality or impulsiveness in general meaning.

In searching for a better noise index, the priority should be to find an adequate rating which would be (1) better associated with annoyance or one of the annoyance scales (2) describe the variance accounted for as much exposure-response relationships as possible. Regarding better association with annoyance Marquis-Favre, Premat, Aubrée, et al. (2005) argue that stronger correlation between annoyance and exposure does not exceed 0.3. On the second issue, exposure-response relationships only account for 20-30% of variance explained it comes to transportation noise (Job, 1988). Any index which can improve description of such relationships would provide the improvement on this matter. Unfortunately, it is probably not feasible that a single rating would enable significant correlations in the analysis of the exposure-response relationship for noise annoyance (Marquis-Favre, Premat, Aubrée, et al., 2005).

One approach to consider would involve a standard that could advocate sets of rules or best practice guidance for noise annoyance research, which states which acoustics measurements and analysis should be conducted. Future studies could therefore be more comparable. In the paper by Fields et al. (1982a) a set of suggestion on a standardised measuring exposure and conducting questionnaire is discussed. European guideline regarding application of L_{dn}, L_{den} in exposure-response relationship is presented by Miedema (Miedema et al., 2001; Miedema, 2007).

In regard of a second approach, Marquis-Favre, Premat, Aubrée, et al. (2005) reviewed a wealth of noise indices used in studies or developed by acousticians. They made an interesting point about the A-weighted scale. It is known that A-weighted sound pressure level is based on 40-phone equal loudness contour that take into account the physiological response of the average human ear, which perceives low and high frequencies less accurately. Although generally C-weighted and B-weighted scales do not have any advantage over A-weighted scale, it is considered by Hardy et al. (1999) that for studies regarding railway traffic noise combination of C-weighted and A-weighted indices may improve description of noise. Hardy et al. (1999) argued that the majority of energy from trains is induced in the lower range of frequency. A combination of C-weighted and A-weighted indices would include effects related to low frequency noise. This is supported by the figures below (Figure 90 and Figure 91).

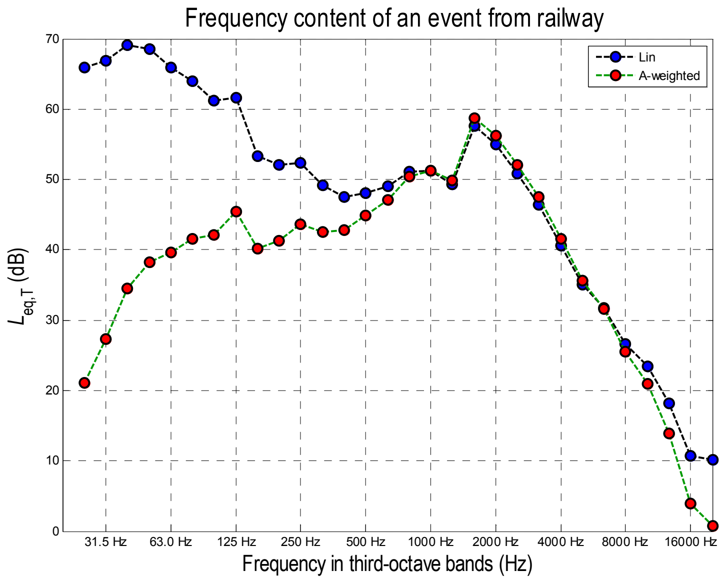

Figure 90. Third-octave band frequency domain signal with A-weighting from a measurement of a passenger train

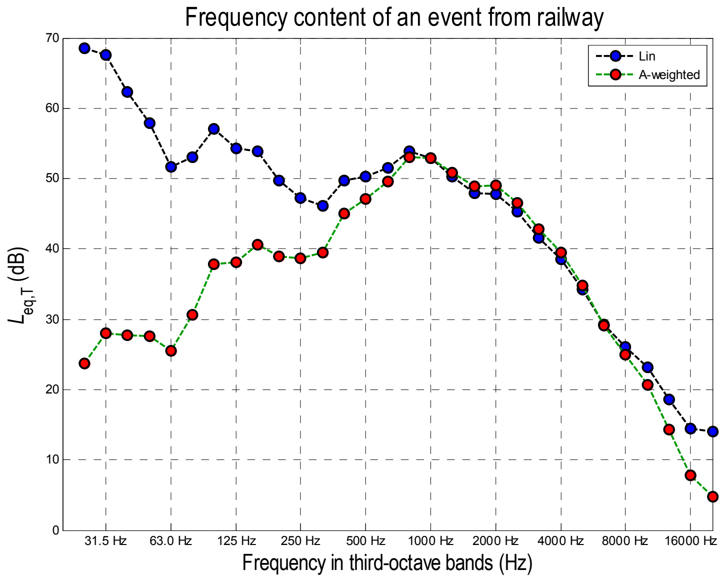

Figure 91. represents third-octave band frequency domain signal with A-weighting from a measurement of a passenger train

Hardy et al. (1999) considered the combination of A-weighting and C-weighting with respect to $L_{\mathrm{Aeq,T}}$. For steady streams of transportation mode such as road traffic, the energy-based noise index such as $\mathrm{L_{den}}$ is commonly accepted. Sound exposure level L_{AE}, on the other hand, was recommended as a major rating for regular acoustic events such as aircraft flybys. In terms of railway traffic, besides lower noise exposure, railway noise may also be considered as a traffic mode of regularly occurred events. In line with considerations from Hardy et al. (1999), L_{AE} in combination with C-weighted scale may also improve exposure-response relationships. According to Marquis-Favre, Premat, Aubrée, et al. (2005) number of studies have used this combination, e.g. Fidell et al. (2000) used it to establish a reliable exposure-response relationship between indoor L_{AE} of aircraft noise events and arousal - an indicator of sleep disturbance.

Considerations were also focused on taking into account fluctuations from noise and combining them with average level of noise. Robinson (1971) conceived a noise pollution level

$$L_{NP} = L_{Aeq,T} + K\sigma \quad \left(\mathrm{dB}\left(\mathrm{A}\right)\right) \tag{7.1}$$

which is the sum of average continuous sound pressure level $L_{\mathrm{Aeq,T}}$ and the standard deviation (σ) of the levels for the same measurement period. Constant K is to adjust the metric due to subjective response to road or aircraft noise. The idea of this rating is to take into account for the increase of annoyance caused by sound pressure level fluctuations. Further studies may include the latter index in combination with previous considerations to investigate its relevance for the human response to railway traffic noise.

7.3. SLEEP DISTURBANCE

Sleep disturbance is undoubtedly one of the most important phenomena investigated now and in the past with regard to annoyance (Basner et al., 2010; Basner et al., 2005; Marquis-Favre, Premat, Aubrée, et al., 2005; Miedema et al., 1999; Ögren et al., 2009; Öhrström, 1997; Öhrström et al., 2006). From social survey questionnaire, sleep disturbance was assessed via face to face interviews where residents were asked whether they were disturbed by noise during night time hours. Data analysis revealed a significant correlation of sleep disturbance with annoyance. To develop a better understanding of the relationship between sleep disturbance and annoyance, ratings such as sleep time period or total time period be considered. For in depth reviews of the relationship between sleep disturbance and noise annoyance see (Basner et al., 2010; Basner et al., 2005). Miedema (2007). More sophisticated methods may require tests conducted on subjects either in their homes with equipment installed in the sleeping-rooms or in an earlier prepared laboratory room where required conditions are maintained.

In the analysing the data on sleep disturbance, an additional issue emerged. As sleep disturbance was assessed with respect to external noise metrics, internal measurements could provide more accurate outcomes. Undertaking internal measurement of noise exposure from railways be difficult in practice. One needs to take into account a location of microphones inside a property which may cause problems regarding room modes at low frequency noise. An example of the attempt to conduct internal measurements of noise exposure is presented in the paper by Graham et al. (2009).

7.4. GROUND-BORNE AND STRUCTURE-BORNE NOISE

The residents in proximity to railways in tunnels are exposed to ground-borne or structure-borne noise. Although this kind of induced noise is regarded as low level, it could become a significantly contributing part of annoyance. Ground-borne noise may invoke annoyance not due to level of noise, but due to frequency content and tonality which has also been found to be annoying (Marquis-Favre, Premat, & Aubrée, 2005). It has been found that

> "below 20Hz, where there is no longer a distinct hearing sensation, sounds are often felt as pulses or vibrations. In these cases people complain of a sensation of anxiety. Between 20 and 60 Hz sounds that are above their corresponding thresholds are often felt as fluctuations. People then complain about a feeling of pressure or vibration. However above 60 Hz, in the normal hearing range, a tonal sound becomes especially annoying" (Marquis-Favre, Premat, Aubrée, et al., p. 627).

Annoyance is a complex phenomenon (See chapter 8 - Appendix A). Studying annoyance as measure of response provides reasonable results, but more could be revealed if other acoustical or non-acoustical variables are also studied. Fields (1993), Marquis-Favre, Premat, Aubrée, et al. (2005), and Miedema et al. (1999) discusses non-acoustical factors, physical factors, and methodology on study of annoyance from noise. Also, with regard to annoyance effect on health, review literature shows report by Berglund et al. (2000), and Berglund et al. (1996).

7.5. PRINCIPAL COMPONENT ANALYSIS

When using a number of acoustical and non-acoustical variables, a principal component analysis (PCA) for categorical data can be performed or standard principle component analysis can be performed if variables are continuous. When ordinal variables are in use, they can be treated as continuous (Coolican, 1999). However, it has to be validated that assumptions of standard PCA are not violated; that is, standard PCA implies that data are linear and normally distributed. The problems associated with standard principal component analysis disappear when categorical PCA is in use.

7.6. STATISTICAL MODEL

The final suggestion considered is with regard to the statistical model used. Vibration and noise exposures were assumed to be from random data completely independent to each other. Unfortunately, variations between sites may cause different responses to the same exposure level invoking higher or lower level of annoyance. A multilevel statistic analysis can attend to issues of variability between sites. In multilevel approach, a model may contain sites associated to different levels in hierarchical structure where particular dwellings would be associated to railways that would be associated to regions, and regions to cities.

The second suggestion is linked to dependent response variables. In this project, combined effects from noise and vibration were restricted to the application of one simple response variable. The case-study project's existing database, contains the following variables: 5-point semantic scale and 11-point numeric scale as a measure of response to noise; and 5-point semantic scale and 11-point numeric scale as a measure of response to vibration. In comparing results between t-test and ANOVAs, *family error* is important (Field, 2009). Family error is related to the reduction of the significance test when a number of groups are compared via a t-test. The family error is

$$\textit{family error} = 1 - (0.95)^N \tag{7.2}$$

where N corresponds to number of compared groups. From this equation, it is evident that comparing three groups separately increases the probability of making a Type I error (*p value*) equal 1 - $(0.96)^3$ = 1 - 0.857 = 0.143. Therefore, probability of making a Type I error increased from 5% to 14.3%. On the other hand, ANOVA does not introduce additional error from separated group comparisons (Field, 2009).

It is possible that similar issues would arise when carrying out separate analyses is conducted for each dependent variable. Therefore, a regression model introducing application of multivariate response would be appropriate. Another advantage of applying a multivariate model, as opposed to a univariate model, is to obtain outcomes that may reveal a relationship between each mutual pairs of response variables. It could be that an additional matrix would enable the control of variables that require mutual analysis. By using this approach, correlation between each semantic and numeric scale would bring important outcomes.

7.7. CONCLUSION

A couple of considerations were included in this section starting from improved noise index, through an expanded statistical model and principal component analysis, finishing with ground-borne and structure-borne noise. The latter suggestion may be important with regard to exposure-response relationship to noise and annoyance reported by participants living in vicinity to tunnel traffic. The other considerations discussed in this chapter provide the potential improvement to results or extra information for the analysis.

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8. APPENDIX A

8.1. ANNOYANCE AND NOISE EXPOSURE

Annoyance is not a simple effect from one or multiple sources. Annoyance is a complex process which occur when vibration, noise, pollution, any other unwanted factor takes place. Some researchers also investigate the combined effects from noise and odour. Miedema (2007) has suggested model of annoyance in his paper.

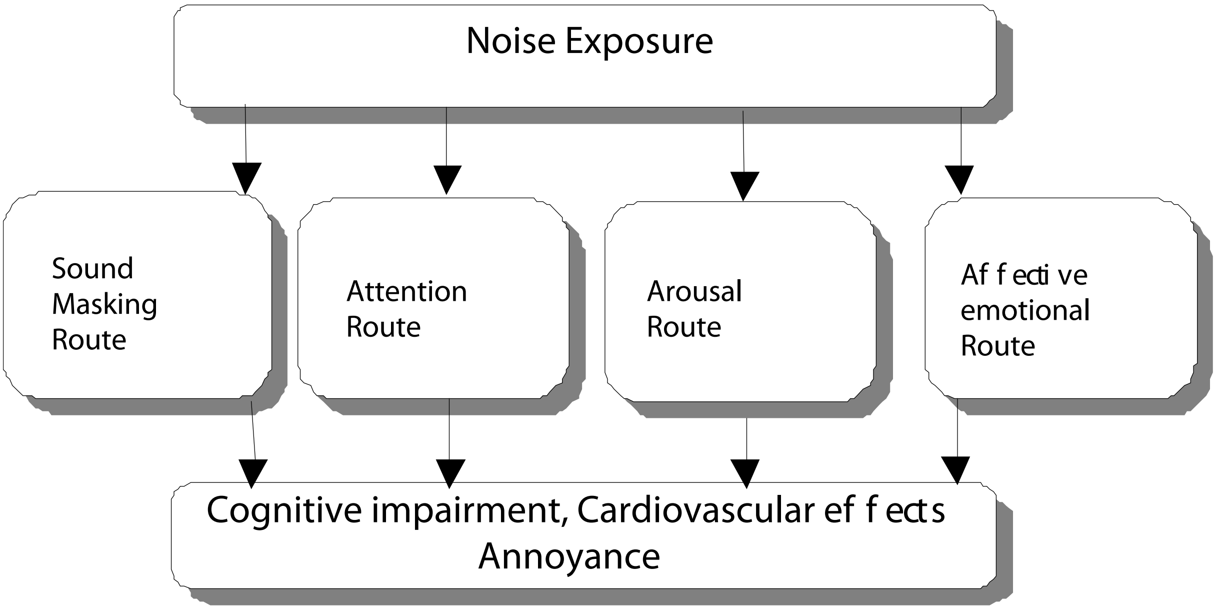


Figure 92. Four routes (primary effects) that contribute with different weights to cognitive impairment, cardiovascular effects, and annoyance. The primary interferences may be accompanied by short-term stress responses and chronic stress may play a role in long-term effects.

has suggested model of annoyance in his paper. His model comprise of four routes distinguished through which noise exerts its primary influence: sound masking (communication disturbance), attention (concentration disturbance), arousal (sleep disturbance), and affective/emotion (fear/anger). Noise annoyance is a sensitive indicator of adverse noise effects and by itself means that noise affects people's quality of life. Therefore it is often taken as an indicator of the acoustical climate (Miedema, 2007). Miedema (2007) discusses this routes and they are detailed in his paper.

In terms of speech, human being feels unpleasant when ability of communicate or retrieve desired sound stimulation or listening music is contaminated by something, the level of annoyance can increase due to unpleasant conditions. Miedema (2007) refers to masking of speech. The lost of concentration can also be annoying. Consequently noise or vibration distracts a person preventing from continuous concentration. This can be frustrating if in presence of noise (Miedema, 2007) or vibration the important task requiring cognitive approach has to be done. It is known that losing concentration severely decreases abilities of any kind that person would effectively use without losing concentration.

Sleep disturbance is probably the most important aspect of annoyance. Tiredness in the morning, number of awakenings, and difficulties of falling asleep make significant increase of annoyance. Listed by Miedema (2007), the noise of a single event can cause effects: extra motility (Fidell et al., 2000) change in sleep state and EEG arousals (Basner et al., 2005; Vallet et al., 1983; Vernet, 1979), momentary change in heart beat parameters (Carter et al., 1994; Hofman et al., 1995; Wilkinson, 1984) and conscious awakening (Fidell et al., 1995; Fidell et al., 2000). The health consequences of instantaneous effects are not yet fully understood. From the list of papers Basner et al. (2010) has shown his studies of the process of sleeping, the sleeping stages changes in the presence of noise.

Fear of damage or being injured permanently is one of the most influential factor (Fields, 1993; Miedema, 2007; Miedema et al., 1999). In terms of aircraft noise, fear is probably more expected in vicinity of airports. In terms of railway, fear of damage due to vibration is more influential than fear due to being impairment that would be caused by exceeding noise. However, if houses are in proximity to rail line, most of all, fear caused significant increase in annoyance.

Moehler (1998) has concluded that in terms of railway exposure, there are, similar in importance, non-acoustic factors or moderators which contribute to annoyance or disturbance. Fields (1979) also studied community response to annoyance from railway in UK. He concluded, similarly to Moehler (1998), that there are non-acoustic factors which increase annoyance. The effect of non-acoustic factors is provided in next section. However, a full analysis will be presented, along with annoyance analysis.

8.2. ANNOYANCE FROM RAILWAY TRAFFIC - COMPARISON WITH CONSTRUCTION WORK

A number of measurements of noise was conducted at sites were construction activity were undergoing. This section is to provide a comparison between annoyance reported from railway traffic and annoyance reported from construction works.

Distribution of number of respondents falling into each annoyance category is provided by four figures. In all cases, most participants reported category "not at all". From Figure 93 and Figure 94, one can conclude that that significantly greater percentage of residents reported the highest annoyance level when noise was caused by construction work.

Another very important aspect regarding percentage annoyed is shown by Figure 95 and Figure 96. Both figures show annoyance levels reported by community being exposed to construction noise at two different circumstances. Figure 95 represents construction work located at longer distance to noise sources. The residential area at that site was situated behind trees and brunches, which somehow separated the residential area from visible noise sources. However, it cannot be said that plants significantly reduced noise exposure. Somehow, something interesting can be observed in Figure 95. Two important bars representing proportion of residents reporting category “not at all” and “extremely” are relatively different from the same bars in Figure 96. It perhaps demonstrates positive influence green plants such as trees or brunches on socio well-being. The bars representing “Not at all” and “Extremely” are in different proportions in Figure 96. Category “Extremely” was reported by greater percentage of respondents when construction activity was in close vicinity to residential dwellings.

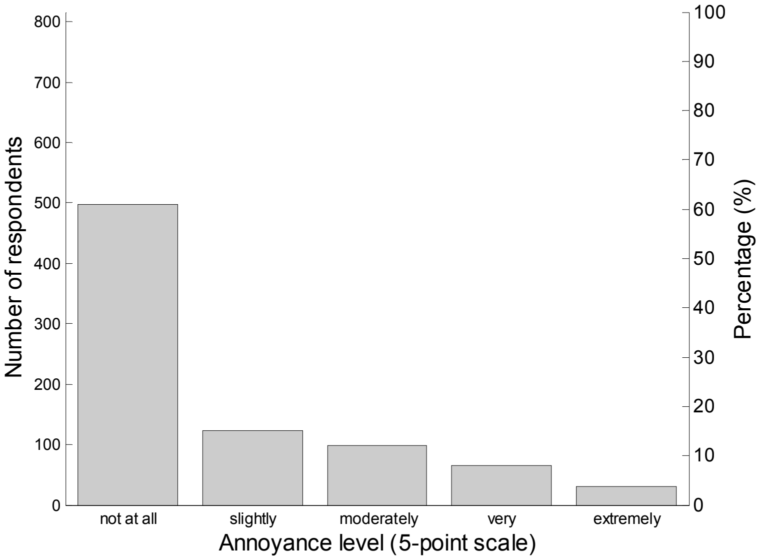


Figure 93. Distribution of number of respondents exposed to noise from railway by five point annoyance scale.

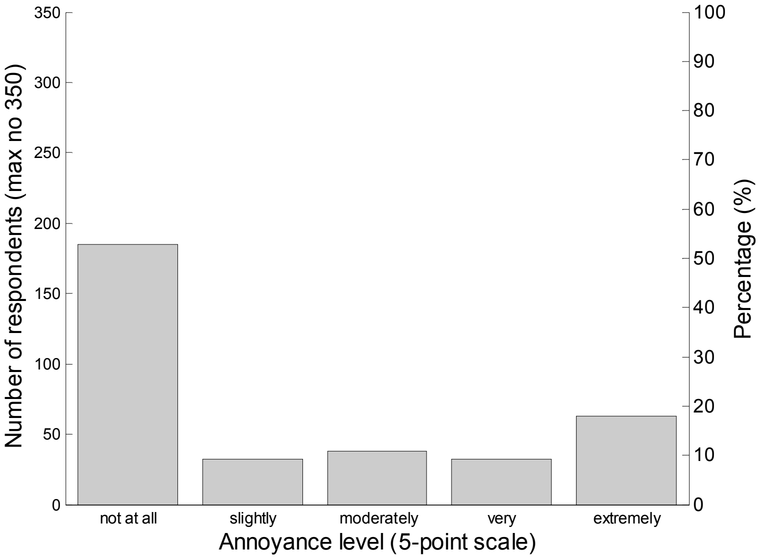


Figure 94. Distribution of number of respondents exposed to noise from construction by five point annoyance scale

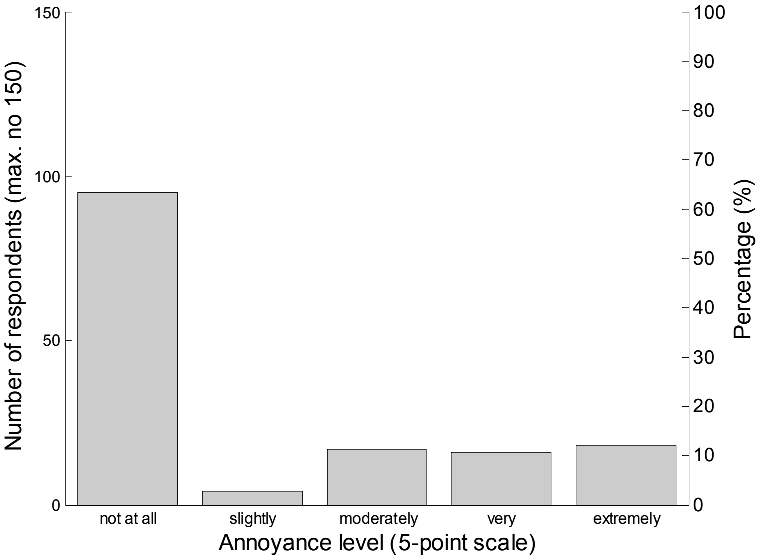


Figure 95. Distribution of number of respondents exposed to noise from construction by five point annoyance scale. The construction work took place in environment behind natural barriers such as trees or branches.

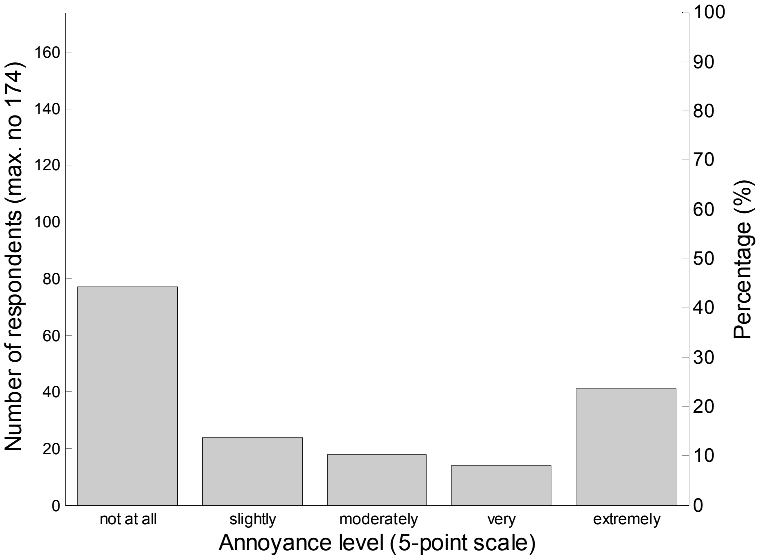


Figure 96. Distribution of number of respondents exposed to noise from construction by five point annoyance scale. The construction work took place in residential area without any obstacles.

9. APPENDIX B

The Table 28 presents summarized results from SPSS function CATPCA which run an nonlinear principal component analysis. There are four different options to choose from to apply optimal transformation names as follows: *Nominal*, *Ordinal*, *Spline Ordinal*, and *Numeric*. As all the data used in this project are ordinal, consequently, *Ordinal* options seem to be the most adequate. However, to investigate that nonlinear PCA results give the highest percentage of variance accounted for, the other options were also investigated and outcomes are presented in the Table 28.

This table is divided into number of rows corresponding to Percentage Variance Accounted For (PVAF), Variance Accounted For (VAR) and Cronbanch's Alpha. First two values represent how much each component or a total sum of all components contribute to variance. These values are determined by inspecting eigenvalues returned by CATPCA. VAF is a simple representation of eigenvalues. The higher is this number, the better contribution to the model. The table also separates results calculated for a full amount of variables from a quantity that seemed to have a significant contribution to the model.

A list of all variables is presented in Table 29. The following variables are included in analysis: three different vibration ratings (VDV, RMS, and Peak), sensitivity, two annoyance scales, distance, demographic variables (age, gender, ethnicity), etc. A number of variables had to be excluded from analysis because. The explanation on this issue is discussed below.

Table 28. Percentage of both total variance accounted for (Total VAF) and variance account for (VAF)

			Nominal	**Ordinal**	**Spline Ordinal**	**Numeric**
All variables included	1st Comp.	PVAF[a]	27.13%	26.98%	26.86%	25.96%
		VAF[a]	3.255	3.237	3.223	3.115
		Cronbach's Alpha	.756	.754	.752	.741
	2nd comp.	PVAF[a]	18.57%	17.03%	16.35%	15.98%
		VAF[a]	2.229	2.043	1.962	1.918
		Cronbach's Alpha	.601	.557	.535	.522
	Total	**PVAF[a]**	**45.70%**	**44.00%**	**43.21%**	**41.94%**
		VAF[a]	**5.484**	**5.280**	**5.185**	**5.033**
		Cronbach's Alpha	**.892**	**.884**	**.881**	**.874**
Variables Excluded	1st Comp.	PVAF[a]	28.06%	28.06%	27.99%	27.18%
		VAF[a]	3.367	3.367	3.358	3.262
		Cronbach's Alpha	.844	.844	.843	.832
	2nd comp.	PVAF[a]	16.12%	16.12%	16.12%	16.06%
		VAF[a]	1.934	1.934	1.935	1.928
		Cronbach's Alpha	.580	.580	.580	.577
	Total	**PVAF[a]**	**44.18%**	**44.18%**	**44.11%**	**43.25%**
		VAF[a]	**5.301**	**5.301**	**5.293**	**5.190**
		Cronbach's Alpha	**.974**	**.974**	**.973**	**.969**

a. (P)VAF - (Percent) Variance Accounted For

Table 29. Centroid and total coordinates with dimensions of variables

	Variance Accounted For					
	Centroid Coordinates			Total (Vector Coordinates)		
	Dimension		Mean	Dimension		Total
	1	2		1	2	
D13_how_concerned_property_damaged	.686	.031	**.358**	.685	.010	.695
D15_how_sensitive_to_vibration	.076	.021	.049	.076	.020	.097
D9_ha_railway	.826	.023	**.424**	.826	.019	.845
D10_rating_annoyed	.741	.029	**.385**	.740	.022	.762
Dist_categ	.009	.017	.013	.007	.010	.018
D16_acceptable_vibration	.763	.025	**.394**	.762	.017	.780
Y3_age_category	.051	.105	.078	.027	.100	.127
Y5_ethnicity	.068	.089	.078	.034	.069	.103
Y6_employment_status	.036	.132	.084	.024	.114	.139
Y9_gender	.001	.000	.000	.001	.000	.001
log_rms_8Hz_categ	.090	.390	**.240**	.088	.390	.478
log_vdv_W_categ	.043	.751	**.397**	.042	.751	.794
log_peak_W_categ	.050	.738	**.394**	.049	.738	.787
Active Total	3.439	2.351	**2.895**	3.363	2.261	5.624

The values were computed by CATPCA with Ordinal option and optimal transformation. The centroid coordinates are shown by Table 29. Unlikely to standard PCA, CATPCA does not extract components based on any criterion. The decision has to be made during analysis. Three criteria found in (Manisera et al.) are considered.

First criterion is very simple. Explained in the book by Field (2009) , this criterion relies on eigenvalues of each component. It essentially suggests that a component is extracted if its eigenvalue is greater than one. Although widely used in analysis, the accuracy of this criterion is questioned. The issue becomes significant when a number of variables is greater than thirty. This is because a number of possible eigenvalues is equal to number of variables originally implemented in model as well as number of components--thirty if there are thirty variables used in a structure. When an eigenvalue is equal one for a component, a component represents 1% of variance explained. The criterion determining a number of components should be therefore based on a percentage of variance explained by a retained number of components. It is useful technique if certain conditions are met. It is also used in elsewhere (Manisera et al.) along with other criteria.

The second criterion is proposed by Cattell (1966) based on investigation of so-called Scree plot. Cattell (1966) suggests that components are to retain if the slope of a Scree plot is stip. After a point of inflexion where the slope changes rapidly all the other components should be removed from analysis.

The third criterion involves interpretation of components already extracted from CATPCA. Because a rotation of loadings is not included in CATPCA function (in opposition to standard PCA), component loadings are used as an input of classic PCA with *varimax* rotation. The rotated components remain uncorrelated with this type of rotation. The decision of a number of components is made by inspection of rotated component loadings and comparing VAF for three and two components.

Before extracting the number of components, in Table 29, section *Centroid Coordinates* displays coordinates for each variable on each dimension in relation to centroid (0,0). By inspecting the table, it can be observed that a few means of Centroid Coordinates are close to centre point indicating that contribution of those variables is very poor. Also, Figure 97 shows this situation in a vector model graph. Basically, a variable is visualized as a vector, whose category points are located on a line whereas the direction is given by the component loadings. Because CATPCA includes nonlinear optimal scaling transformations, the vector model (Figure 97) does not represent the original categorical variables but the transformed variables. Similarly, it can be noticed that vibration ratings, sensitivity, two annoyance scales, distance, demographic variables does have a poor association with components.

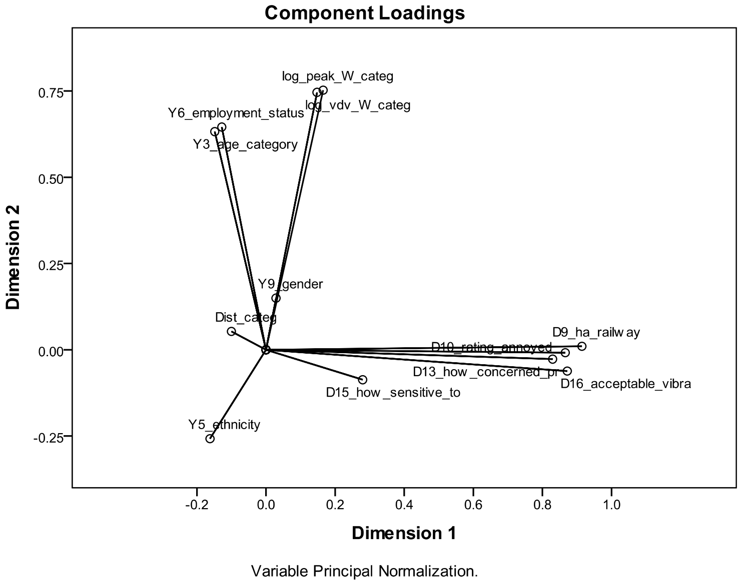


Figure 97. Vector model of two component loadings. Some variables such as ethnicity, sensitivity, distance, and gender are close to origin point indicating their very weak association with any of the two components.

9.1. NONLINEAR PRINCIPAL COMPONENT ANALYSIS OF REDUCED NUMBER OF VARIABLES

Due to above-mentioned issues, the model was reduced to a number of variables which have significantly stronger association with components. First of all, inspecting Table 28, one can observe that four optimal transformations was investigated in terms of percentage of variance accounted for, as well as Cronsbach's α. VAF is a measure of how much variation is explained by a retaining number of components. This is determined by specifying an eigenvalues of each component and its total value that is a sum of eigenvalues from each component. The table also contain PVAF[9] indicating Percent VAF. By inspecting Table 28, it should be noted that *Nominal* and *Ordinal* optimal transformations give the highest amount of variance explained. Due to an ordinal character of variables, *Ordinal* scaling is chosen for further analysis.

---

[9] PVAF is calculated from the following formula:

PVAF = (Eigenvalue / number of variables) x 100%

9.2. PRINCIPAL COMPONENT EXTRACTED

It can be observed from the Table 30 that an eigenvalue for the third component is less than one. According to Kaiser's criterion, this is a candidate to be excluded from analysis--this approach may become inaccurate due to the above-mentioned issues.

Table 30. Results from Nonlinear PCA with three components to extract

Model Summary

Dimension	Cronbach's Alpha	Variance Accounted For
		Total (Eigenvalue)
1	.832	3.265
2	.577	1.927
3	-.229	.841
Total	1.001[a]	6.033

a. Total Cronbach's Alpha is based on the total Eigenvalue.

Another test involves inspecting the Scree plot Cattell (1966) shown by Figure 98. According to Cattell (1966), points of inflexion is a threshold determining a number components for exclusion. In Figure 98, the eigenvalue of this point is 0.559. This means that both criteria proposed by Kaiser's and Callett's does not provide the exact outcome. However, it is assumed that Kaiser's criterion is more accurate.

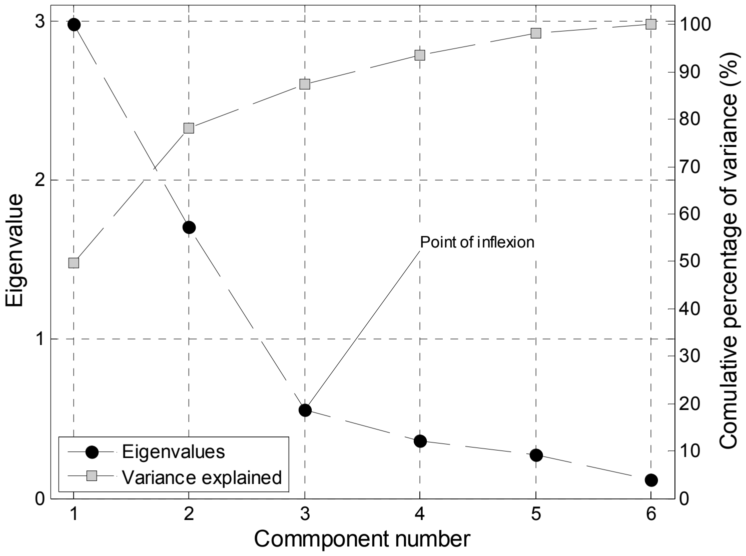


Figure 98. Scree plot presenting components' eigenvalues and corresponding variance explained. A model was reduced in a number of input variables (from 12 to 6, see Table 29).

Figure 99 presents vector model after excluding all variables which do not significantly contribute to the model. A clear distinction of two components can be seen. On one hand, the first component contains variables of similar meaning expressing annoyance in two scales (5-point semantic and 11-point numeric scale) along with a concern about damage of a property and acceptable of vibration. On the other hand, the second component contains only exposure of vibration. From this figure, the structure of data can be divided into two sections. The first one describes vibration exposures whereas the second the reaction to this exposure. The variables such as age, gender, sensitivity (this is rather surprising), distance (issues regarding computation of L_{den}), employment status, and ethnicity were eliminated because of a poor contribution.

Table 31. VAF for two component extracted by CATPCA.

Variance Accounted For

	Centroid Coordinates			Total (Vector Coordinates)		
	Dimension		Mean	Dimension		Total
	1	2		1	2	
D13_how_concerned_property_damaged	.749	.019	.384	.749	.001	.750
D16_acceptable_vibration	.802	.013	.408	.802	.006	.808
D9_ha_railway	.942	.017	.479	.942	.012	.954
D10_rating_annoyed	.826	.021	.423	.826	.012	.838
log_vdv_W_categ	.023	.953	.488	.022	.953	.975
log_peak_W_categ	.029	.950	.489	.027	.950	.977
Active Total	3.371	1.972	2.671	3.367	1.934	5.301

The greater attention is required for to investigate sensitivity because, according to Miedema et al. (2003) and Fields (1993), this factor is very important and influential on annoyance.

Two sets of transformation plots can be found in both Figure 100 and Figure 101. The first set illustrated by Figure 100 is the results from *Ordinal* outcome. On the other, hand the second set illustrates similar graphs after the *Nominal* quantification. The two sets are presented in order to provide comparison between ordinal and nominal transformations. If, for any reason, data did not show natural ordinal character when they suppose to, it is believed that this problem would come out after nominal quantification that could found in second sets of graphs. After optimal scoring, ordinal data should produce monotonic functions (See Figure 101). By comparing two sets, almost each graph contains monotonically increasing functions, apart from the middle right-hand site graph. This indicates that data have an ordinal character. The latter characteristic is in accordance with descriptive statistics presented in two sections: the presenting and discussing results (See chapter 5) and the chapter providing explanation on response scales (See chapter 3.2).

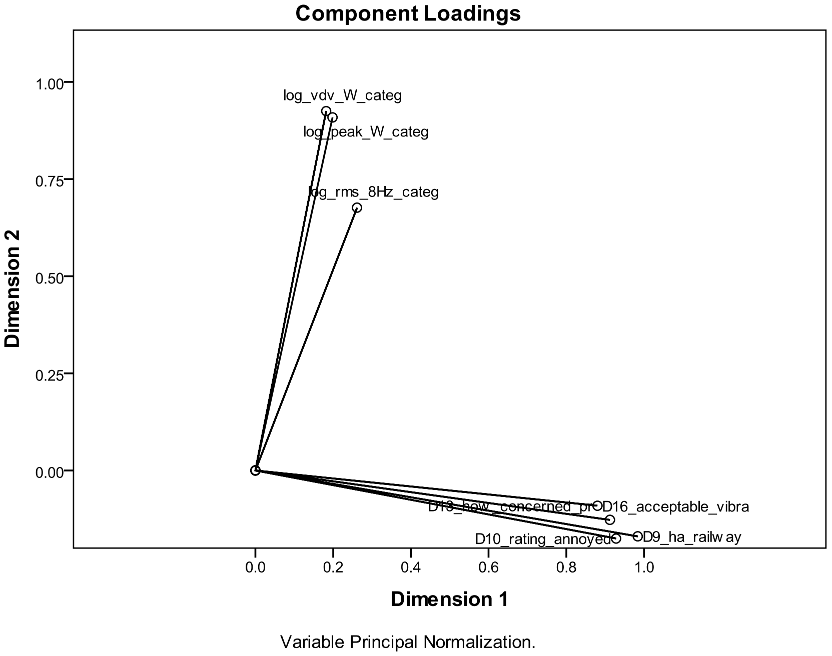


Figure 99. Vector model similar to Figure 97 presenting loadings in two-dimensional space. All variables of poor contribution were excluded from the model.

A couple of the other features can be seen by inspecting graphs in Figure 100 (Figure 101 was drawn only due to validation for an ordinal character of data). All graphs display non-linear transformation. This means that perhaps standard PCA would result with non-accurate outcomes. The optimal quantifications are given on the vertical axes versus the original values on the horizontal axes. For all graphs, the non-linear transformations show convexity, indicating that there is a less distinction between lower categories, with higher contrast and greater distinction at higher categories. All categories at close to zero indicate to be close to mean.

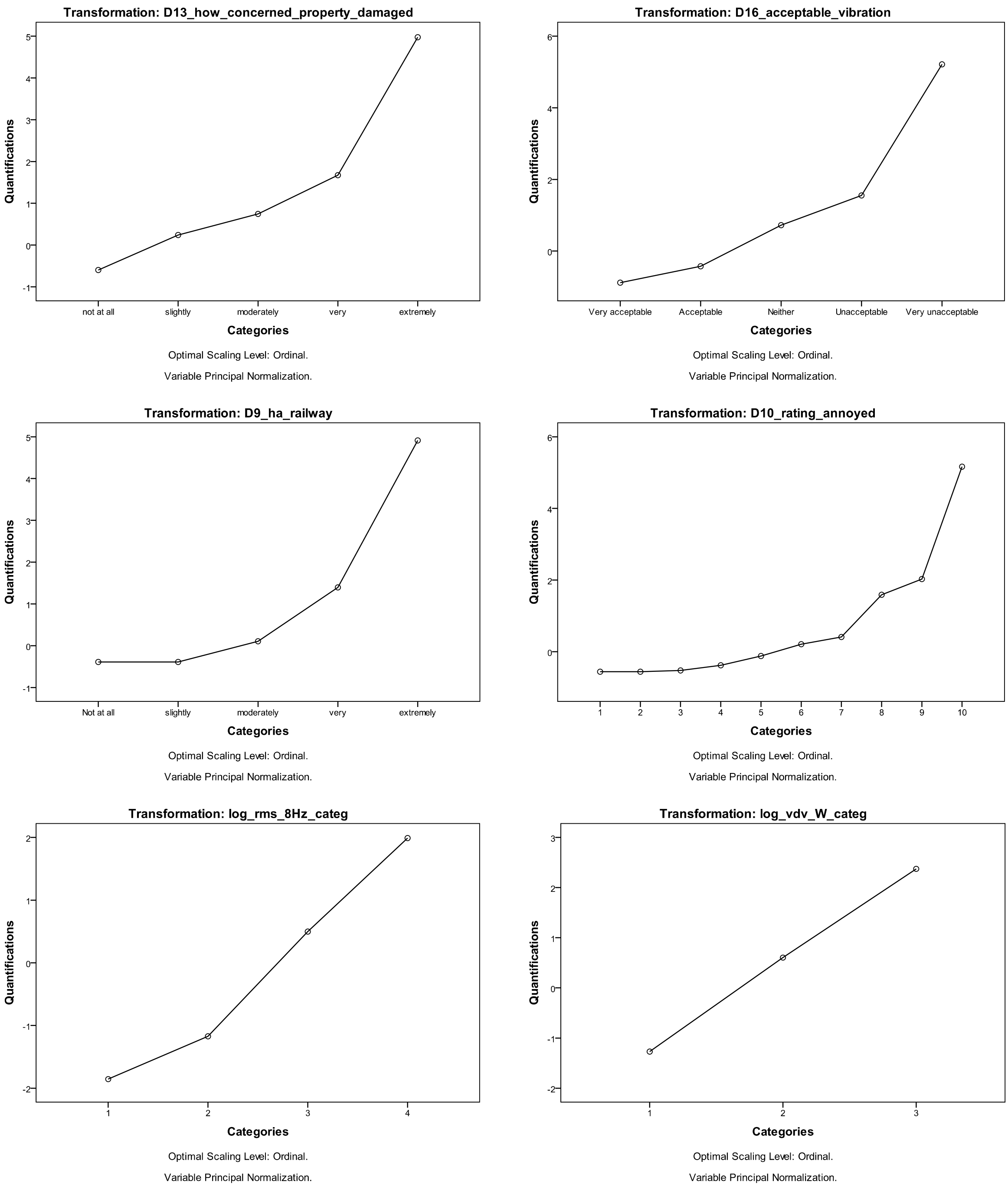


Figure 100. The set of figures representing Ordinal solution after undertaking nonlinear PCA in SPSS.

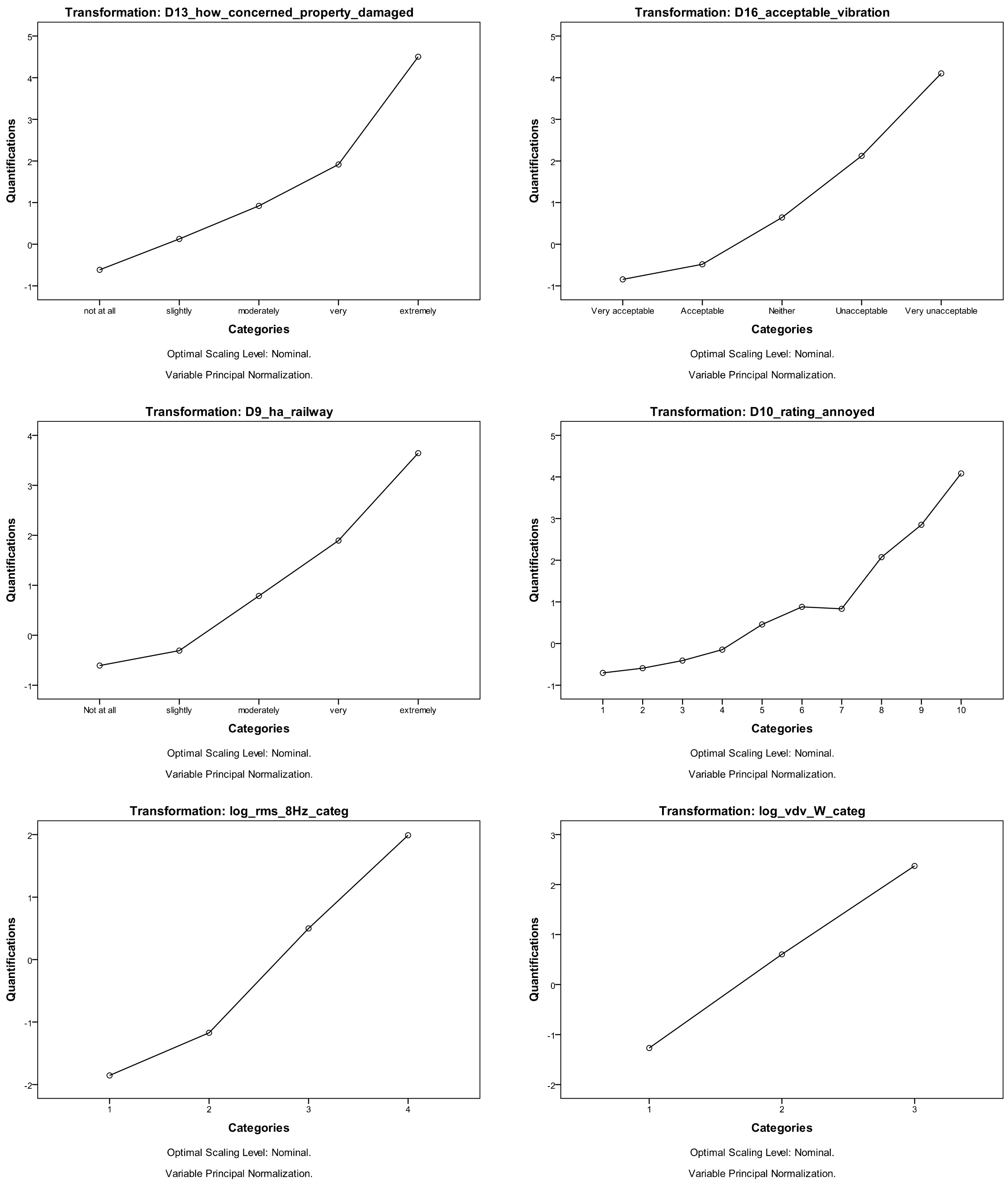


Figure 101. The set of figures representing Nominal solution after undertaking nonlinear PCA in SPSS.

10. APPENDIX C

PROCEDURE TITLE:		**Procedure for the measurement of railway vibration in residential environments**			
PROCEDURE NO:		**PP09**			
First Issued:	09.09.09	**Last Revised:**	20.11.09	**Revision No:**	3
Document Filename:		V:\SF\CSE\NANR209\Quality Manual\Procedures\PP09_03.doc			

1 Purpose

This procedure defines the process used by the technical team to measure vibration affecting occupants of a residence located near the railway, in order to assess the human response due to vibration produced by trains.

2 Scope

This procedure applies to railway vibration perceived by people who are exposed to whole-body vibration at home.

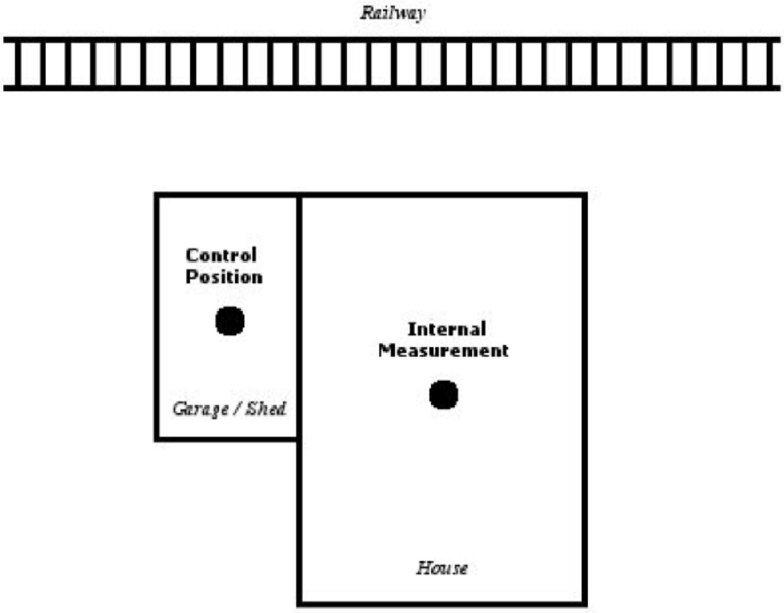
3 Responsibility

Members of the technical team are responsible for ensuring this procedure is followed when carrying out field measurements.

4 Measurement Procedure

4.1 Introduction

The measurement technique required to assess human response to vibration produced by railway traffic uses the following measurement concept as a basis for the measurement. The diagram represents a house facing a railway. A long-term monitoring measurement is made at the control position and a synchronized short-term measurement is taken inside the building (the internal position).



4.2 Control measurement position

Select a secure location in the near field of the railway to position the 24-hour control measurement. The control position should be set up in the resident's garage or garden shed if possible as these places are generally quieter and closer to the railway than the habitable space.

4.3 Mounting control accelerometer

Mount the Guralp accelerometer according to Section 5. Use a compass to orientate its arrow towards north. Connect the instrument to the external battery, attach the GPS antenna and leave it to record for at least 24 hours.

4.4 Completing control measurement proforma

Complete the proforma PMV1. Record all information regarding the measurement.

4.5 Internal measurement position

Position the second Guralp accelerometer to record a short internal measurement inside a property within a radius of 50m of the control position. The internal measurement should be taken near the centre of the room in which the respondent states they can feel the highest magnitude of vibration. In the case that the respondent states that they cannot feel vibration within the property, the Guralp units are preferably mounted directly in the centre of a ground floor room with a rigid floor.

If the respondent does not allow an internal measurement then an external measurement should be taken as described in section 4.6.

4.6 External measurement position

If the respondent is at home and does not allow an internal measurement an external measurement should be taken as close to the foundations of the house as possible, if the respondent allows doing so.

If the respondent does not allow any measurement close to the property or is not at home the external measurement has to be taken in the pavement of the street in the front or in the back of the property.

4.7 Mounting internal accelerometer

Mount the Guralp accelerometer according to Section 5. Use a compass to orientate its arrow towards north. Connect the instrument to the external battery, attach the GPS antenna (if possible) and leave it to capture a recording of at least 4 passing trains.

4.8 Mounting external accelerometer

Mount the Guralp accelerometer on the pavement. Use a compass to orientate its arrow towards north. Connect the instrument to the external battery, attach the GPS antenna (if possible) and leave it to capture a recording of at least 4 passing trains.

4.9 Completing internal measurement proforma

Complete the proforma PMV1. Record all information regarding the measurement.

4.10 Completing external measurement proforma

Complete the proforma PMV1. Record all information regarding the measurement.

4.11 Collecting internal measurement accelerometer

Collect the second Guralp accelerometer from the property and conduct the “heel drop test” as described in section 6.

4.12 Further Internal measurements

Repeat the internal procedure (from section 4.5 to 4.8) for other properties if needed.

4.13 Collecting control measurement accelerometer

After at least 24 hours and when all internal measurements have been made, collect the control position accelerometer and conduct the “heel drop test” as described in section 6.

5 Mounting method

5.1 Mounting position

Mount the Guralp units, where possible on the centre of a rigid floor.

5.2 Mounting surface

If the floor is wooden, mount the Guralp unit as close as possible from the centre of the beam.

If the covering surface is carpet, mount the Guralp unit on the steel plate to dampen any mounting resonances setup between the accelerometer and the compliant surface.

6 Heel drop test

6.1 Unloaded heel drop

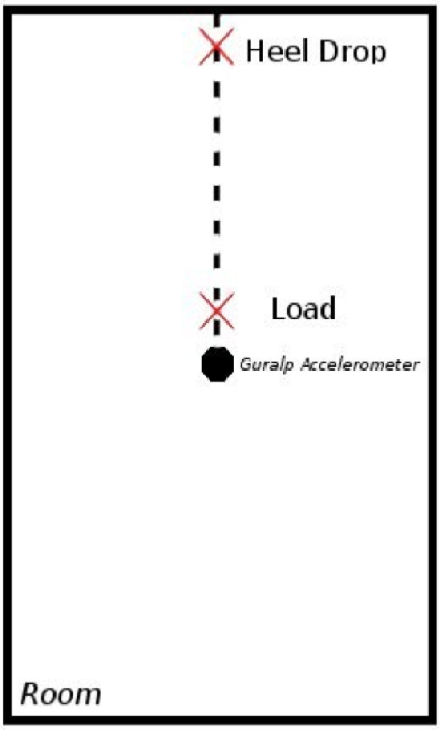
A member of the measurement team has to stand aligned with the accelerometer, as far as possible from it (if it is a wooden floor the person has to stand in the same beam as the accelerometer) and conduct a heel drop (put in his/her tiptoes and leave his/her weight till the heal touches the floor again).

6.2 Loaded heel drop

Repeat the section 6.1 with the house holder loading the floor. The house holder should be standing 10cm away from the instrument, facing the person that conducts the heel drop test. In the case that the house holder can not participate in the test, another member of the vibration team should load the floor.

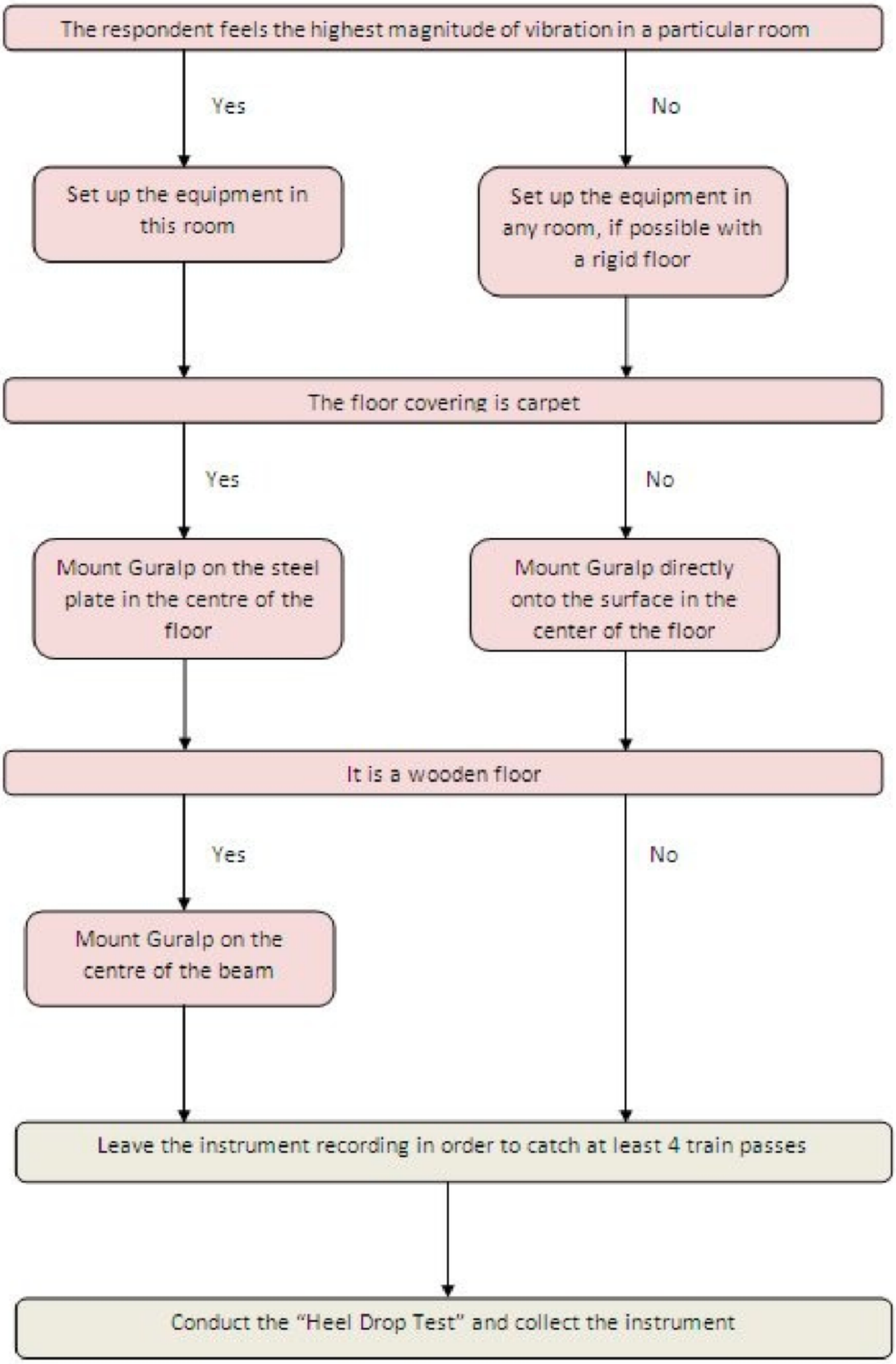
6.3 Completing measurement proforma

Record all the details regarding to the test on the proforma PMV1.

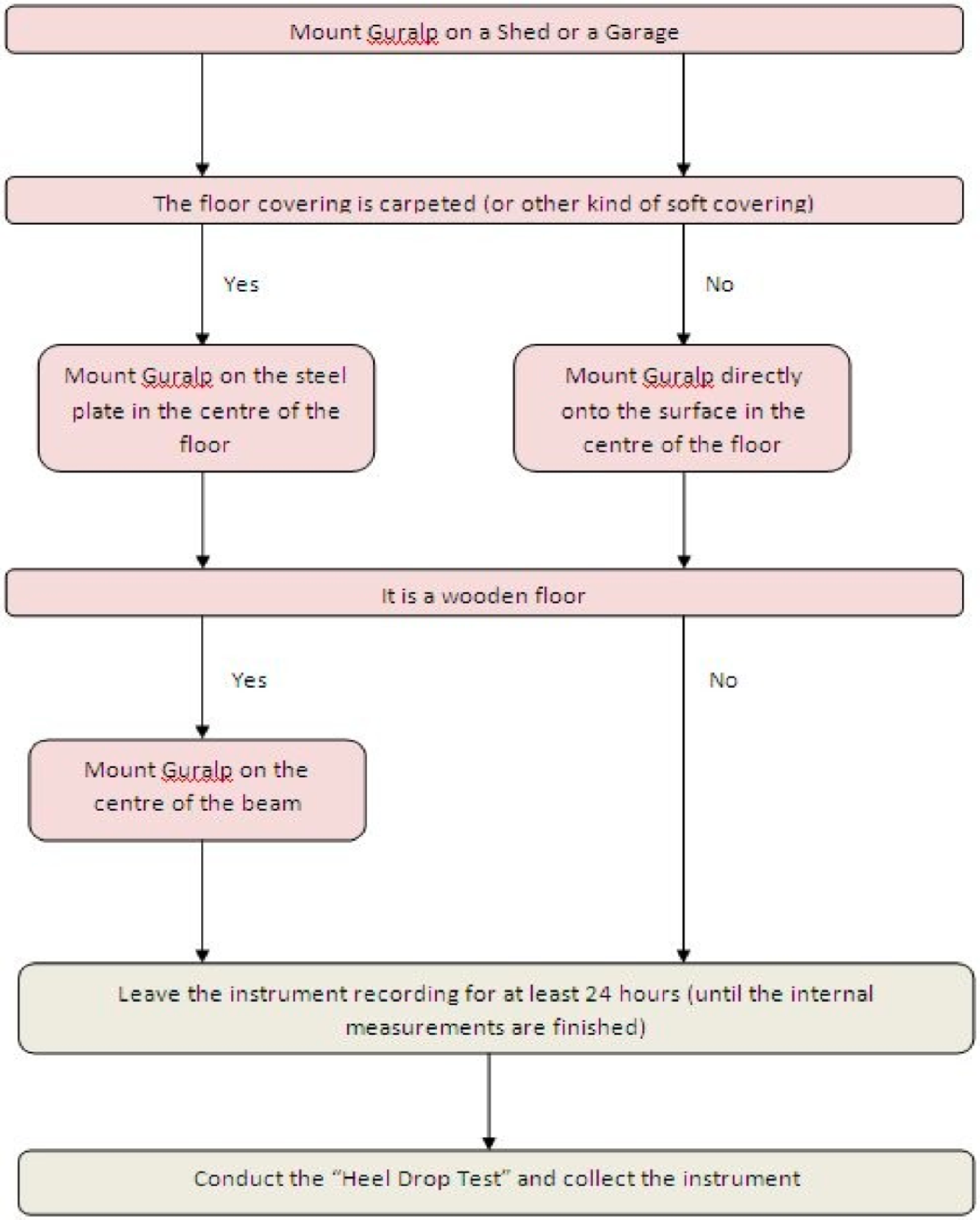


7 Schemes

7.1 Internal measurement scheme



8 Control measurement scheme



9 References and Associated Documents:

BS 6472-1:2008

ANC Guidelines (Measurement & Assessment of Groundborne Noise & Vibration)

11. APPENDIX D

1 UNIVERSITY OF SALFORD

Research Governance and Ethics Committee

1.1 Ethical Approval Form for Staff

Ethical approval must be obtained by all staff prior to starting research with human subjects, animals or human tissue. The member of staff must show and if necessary discuss the content of this form with the Research Institute Director before it is 'signed off'.

If the application for ethical approval is part of a bid for external funding, the form must be completed as a supplement to the Budget Approval Form.

The signed Ethical Approval Form must be forwarded to the Contracts Office and an electronic copy emailed to the Research Governance and Ethics Committee via Max Pilotti (m.u.pilotti@salford.ac.uk).

Please refer to the 'Notes for Guidance' if there is doubt whether ethical approval is required.

(The form can be completed electronically; the sections can be expanded to the size required)

1.1.1 Name of member of staff : Dr. David Waddington

School : **School of Computing, Science & Engineering**

Research Institute : **Built and Human Environment**

Name of Research Council or other funding organisation (if applicable):

Defra

1a. Title of proposed research project

Research into the human response to vibration in residential environments

1b.

Is this Project Purely literature based?

~~YES~~ / NO (delete as appropriate)

2. Project focus

The project will develop a method by which human annoyance to vibration in residential environments can be assessed.

3. Project objectives (maximum of three)

The Objective is to perform a social survey and measurements of environmental vibration. Specifically, this project has the following objectives:

i. to review and refine the main study protocol, originally developed by Defra in a pilot study,

ii. to conclude as to whether a dose-response relationships exist for various vibration sources, based upon a statistically robust social survey questionnaire sample size,

iii. to determine such indices relating vibration measurements with human annoyance in residential environments.

4. Research strategy

(For example, where will you recruit participants? What information/data collection strategies will you use? What approach do you intend to take to the analysis of information / data generated?)

Our strategy to meeting the aims and objectives will be to complete the following main stages:

1. Review of the pilot study
2. Refinement of measurement protocol and social survey questionnaire
3. Main study, including site work and data analysis
4. Preparation of the final report

The individual project activities within each of the four main stages are detailed below.

2 REVIEW OF PILOT STUDY

An understanding of best-practice in social survey in questionnaire design is essential for this project. In particular, the appropriate statistical analysis associated with this academic field requires a particular speciality. This task will be headed by Dr. Mags Adams who has experience of confidentiality and traceability in publicly sensitive projects, in collaboration with Dr Phil Brown of SHUSU. This combination of experience is ideally suited to the supervision of the social survey and questionnaire components of the project.

It is intended that this review of the pilot study result in the finalisation of the measurement protocol and of the social survey questionnaires. However, some issues regarding the measurement protocol require investigation beyond the scope of this review of the pilot study. These issues will be resolved in Stage 2, as detailed below. Similarly, issues regarding the analysis methodology will require study beyond the scope of this stage, so will also be discussed in Stage 2.

3 REFINEMENT OF METHODOLOGY

The first step in refinement of the measurement protocol, social study questionnaire and analysis methodology will require detailed analysis of pilot study field data. The second step in this stage is to implement the recommendations of the pilot study report, to produce the finalised protocol. The final step of this stage is an analysis of the uncertainties in the finalised protocol through a short series of preliminary case studies. At the end of this stage a report will be produced with case studies using the refined protocol analysed using postulated dose-response relationships. It should therefore be clear within the first year whether the project is likely to achieve its overall objectives.

3.1 Postulation of dose response relationships

A further objective of the review of measurement data from the pilot study is to look for a dose-response relationship. The pilot study report implies that significant correlations between annoyance and vibration magnitude gave evidence of a dose-response relationship. Indeed, it is stated that a large volume of data was acquired, but relatively little analysis was undertaken. A specific analysis of the pilot study recordings to examine the correlation between annoyance and a range of vibration parameters could provide valuable information about the suitability of different parameters to be examined in this project.

Vibration measurements will be made under highly controlled conditions with the objective of investigating the variability of transfer functions between external and internal transducer positions. The Structures and Materials Laboratory at the University of Salford is one of the major facilities for structural testing in the UK. It is situated in the laboratory next to the Acoustic Test facilities.

3.2 Refinement of the social study questionnaires

It is proposed that the social study questionnaires be revised to more specific to the type of measurement site. It is suggested that measurements will be made at construction sites, near railways, by the side of roads, and around piling operations. These external vibration sources have been carefully chosen since they have both similarities and differences. This means that the regions of validity of the dose-response relationship or relationships derived can be examined. Consideration will also be made for application to internal vibration sources. Consequently, a shortened questionnaire will be produced to be more site-relevant.

A fundamental review of the analysis strategy for the questionnaire results will be undertaken. This review and subsequent refinement will be undertaken by the university specialists in SHUSU working under the direction of Dr Phil Brown in co-ordination with Dr Mags Adams. The accuracy of the strategies employed using the refined social study questionnaires will be quantified.

3.3 Conclusions from the refinement the measurement protocol and social study questionnaire

Following the refinement of the measured protocol, social study questionnaires, and analysis methodology, the finalised protocol will be used in a set of preliminary measurements. These will take place with subjects and a location suitable for inclusion in the final study. The complete process from identification of suitable measurements sites, through measurement and data analysis to postulation of a dose-response relationship will be performed. An important conclusion from this preliminary measurement implementing the recommendations of the report could be to highlight shortcomings in the fundamental methodology

4 MAIN STUDY

4.1 Identification of case studies

Regarding suitable measurements sites, we will initially identify a number of sites through contacts known to the University of Salford. Professional contacts and the Defra working group will be approached in order to identify appropriate measurement sites that may be engaged.

4.2 Justification of sample size

Regarding the sample size of 2000 completed cases of questionnaire and accompanying measurements, it is considered that this number is well chosen to achieve the project objectives. As mentioned above, it is proposed to measure vibration sources that have similarities and differences: namely construction sites, piling operations, railways, and roads. This means approximately 500 case studies per vibration source. Within each vibration source, the project variables to be considered include age, gender, and time of day, but also consideration will be given to construction type and floor covering. Within the variable of age, assuming a range of 20-80, this approximates to ~60 case studies per decade, and so 30 case studies per gender per decade. Allowing for failed measurements and variability in correlations, this is a robust statistical sample size. Should the methodology prove to be particularly efficient at yielding good responses from residents, more case studies may be obtained for the four vibration sources proposed.

4.3 Social survey questionnaires

The refined social survey questionnaires are expected to be shorter than those used in the pilot study as they will be site-specific. Since the social studies and questionnaires component is the more demanding and time critical constituent of the project, SHUSU have been engaged to deliver these tasks since they have special expertise in this area. It is expected that the social survey questionnaires will be performed while the vibration team are on site although not necessarily present.

4.4 Vibration measurements

This section assumes that the methodology proposed in the pilot study report can be refined and shown to be suitable for the development of a dose-response relationship. The existing proposed methodology recommends external and internal measurements be made wherever possible. It is propose that in addition to the control measurement, two sets of external and internal measurements are performed simultaneously.

4.5 Analysis of social survey questionnaire data and vibration data

The refined analysis methodology will be applied to the social survey questionnaire and vibration data as soon as it becomes available. The objective is to establish and develop the dose-response relationship or relationships for human annoyance to vibration for each vibration source as the project progresses. These assessments will be made with reference to the particular situation, such as numbers of subjects, age, gender, time of day, vibration source, location of receiver, and construction type.

5 REPORTING / MANAGEMENT

Reporting and meetings will follow the requirements of the project Specification provided by Defra. The appointed Project Manager is Dr David Waddington.

5. What is the rationale which led to this project

(for example, previous work – give references where appropriate)

In order to determine the level of disturbance to an individual caused by given vibration, it is necessary to ask them how much they are disturbed. Consequently, levels of environmental vibration will be measured and correlated against the results for a social survey questionnaire.

This work follows an earlier pilot study performed by ARUP and the University of Southampton on behalf of Defra, the results of which provided a methodology for undertaking this wider study to yield a robust relationship between vibration exposure and response. The methodology is detailed in the pilot study report, publicly available from the Defra website: http://www2.defra.gov.uk/science/project_data/DocumentLibrary/NO01106/NO01106_5402_FRP.pdf

6. **If you are going to work within a particular organisation do they have their own procedures for gaining ethical approval**

for example, within a hospital or health centre?

YES / ~~NO~~ (delete as appropriate)

If YES – what are these and how will you ensure you meet their requirements?

This research is to be performed for Defra. Therefore, this research will be subject to all ethical procedures they have in place. To this end, Defra has formed a project board of key advisers, and a series of meetings and reports have been scheduled to monitor this and other aspects of the research project.

7. Are you going to approach individuals to be involved in your research?

YES / ~~NO~~ (delete as appropriate)

If YES – please think about key issues – for example, how you will recruit people? How you will deal with issues of confidentiality / anonymity? Then make notes that cover the key issues linked to your study

The methodology for undertaking this wider study was defined by the pilot study. It involves face-to-face interviews administering a prescribed social survey questionnaire with adults in their homes. Confidentiality and anonymity are ensured by identification on the questionnaire of the address and by a serial number only. People are to be recruited by cold-calling following a door-to-door leaflet drop.

The full multi-part questionnaire is detailed in Appendix D of the Defra report. However, as detailed above, the first stage of the research project will involve refinement of the questionnaire. As part of the refinement, it is proposed to reduce the length of the questionnaire to be administered by making it source specific, e.g., addressing solely construction, rather than road and rail transportation and other sources.

8. More specifically, how will you ensure you gain informed consent from anyone involved in the study?

The measurement protocol developed in the pilot study requires that following initial agreement to help with the survey, a letter is handed to residents outlining the nature of the project and survey work. The main text from the Letter to Residents is detailed in Appendix E1 of the Defra report. The text will be modified to remove reference to the University of Southampton and the other pilot study contractors, and to replace this with the University of Salford. It is also proposed to reduce the length of the letter, to simplify the explanation, and to include a space for respondents to sign acknowledging consent.

9. Are there any data protection issues that you need to address?

YES / ~~NO~~ (delete as appropriate)

If YES what are these and how will you address them?

The above mentioned letter to residents contains a section detailing the Data Protection – Fair Collection Notice, together with a relevant note concerning the Data Protection Act 1998. In addition, confidentiality and anonymity are ensured by identification on the questionnaire of the address and by a serial number.

10. Are there any other ethical issues that need to be considered? For example - research on animals or research involving people under the age of 18.

No

11.

(a) Does the project involve the use of ionising or other type of "radiation"

~~YES~~ / NO

(b) Is the use of radiation in this project over and above what would

normally be expected (for example) in diagnostic imaging?

~~YES~~ / NO

(c) Does the project require the use of hazardous substances?

~~YES~~ / NO

(d) Does the project carry any risk of injury to the participants?

~~YES~~ / NO

(e) Does the project require participants to answer questions

that may cause disquiet / or upset to them?

~~YES~~ / NO

If the answer to any of the questions 11(a)-(e) is** YES**, a risk assessment of the project is required.

12. How many subjects will be recruited/involved in the study/research? What is the rationale behind this number?

From the detailed project specification produced by a Defra, a wide scale study of ~2000 case studies is required to be produced. It is considered that this number is well chosen to achieve the project objectives. As mentioned above, it is proposed to measure vibration sources that have similarities and differences: namely construction sites, piling operations, railways, and roads. This means approximately 500 case studies per vibration source. Within each vibration source, the project variables to be considered include age, gender, and time of day, but also consideration will be given to construction type and floor covering. Within the variable of age, assuming a range of 20-80, this approximates to ~60 case studies per decade, and so 30 case studies per gender per decade. Allowing for failed measurements and variability in correlations, this is a robust statistical sample size.

Please attach:

- A summary in clear / plain English (or whatever media/language is appropriate) of the material you will use with participants explaining the study / consent issues etc.
- A draft consent form – again in whatever media is suitable for your research purposes / population.
- A copy of any posters to be used to recruit participants

Remember that informed consent from research participants is crucial, therefore your information sheet must use language that is readily understood by the general public.

Projects that involve NHS patients, patients' records or NHS staff, will require ethical approval by the appropriate NHS Research Ethics Committee. The University Research Governance and Ethics

Committee will require written confirmation that such approval has been granted. Where a project forms part of a larger, already approved, project, the approving REC should be informed about, and approve, the use of an additional co-researcher.

I certify that the above information is, to the best of my knowledge, accurate and correct. I understand the need to ensure I undertake my research in a manner that reflects good principles of ethical research practice.

Signed by Member of Staff	

Date	

In signing this form I confirm that I have read the contents and I am satisfied that the project can proceed subject to approval by the University of Salford RGEC.

Signed by RI Director	

Date	

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